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Thesis Advisor: Warren W. C. Thompson

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Ocean Wave Group Analysis

by

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Lieutenant, United States Navy
B.S., Oregon State University, 1972

Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

A computerized method for the identification of wave groups and determination of their properties from digital wave data was developed. Analysis was performed on 208 Southern California wave records. It was found that the number of waves in a group is independent of both the spectral peak period and the variance of the wave record. However, the amount of energy contained in wave groups relative to that in the record increases as the total energy of the record increases. Also, average group periods of greater than the spectral peak period are not uncommon. Both an increase in group energy relative to the wave record and also the number of waves in a group increase the possibility of obtaining an extreme wave height in a group relative to the significant wave height of the record. Finally, it is apparent that as the average group period approaches the spectral peak period of a record, all other highly dependent wave group properties take on their maximum values.

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I. INTRODUCTION

One of the dominant features of ocean waves is the occurrence of wave groups. The existence and properties of wave groups have become increasingly important for economic reasons. Groups of large waves have been damaging to coastal structures, both man-made and natural. Surf zone water level fluctuations (surf beat) and current variations are also related to wave groups. Induced seiching in harbors may occur, which may lead to stress on moored craft, and in extreme cases to flooding of adjacent land areas. Wave groups influence the response of ships at sea. The literature devoted to this topic has been fairly sparse in the past, but an increasing interest is becoming apparent. Papers dealing specifically with the definition, occurrence, and properties of wave groups include Goda (1970), Thompson (1972), Ewing (1973), Smith (1974), Siefert (1976), and Chou (1978).

Properties that are considered to define "wave groups" are: (1) groups consist of consecutive large waves, and (2) the waves contained within a group are nearly periodic. In this study a simple method is developed, which can be performed with computer assistance, for the identification of wave groups in a wave record. The method involves analysis of wave records with a type of rms smoothing filter. The smoothed record is then used to identify groups and determine appropriate measures of wave group properties. The smoothing mechanism is a sliding short-term variance. Relationships are then probed between wave group measures and wave record measures, and lastly, the interrelationships of the different wave group measures are examined. The analyzed wave records contain ocean swell representing a wide range of wave steepness, and were recorded on the Southern California coast.

II. WAVE GROUP DETERMINATION

A. FOUNDATIONAL CONSIDERATIONS

There are two fundamental approaches to the analysis of wave records, an analog method which is concerned with distributions of wave maxima and minima, i.e., crests and troughs that occur at irregular time intervals, and a digital method which allows examination of wave records at equally spaced time intervals without regard to crests and troughs. The latter approach is used in this investigation to define and identify wave groups, and to measure their energy content.

To process wave data in a search for wave group properties through the use of a computer requires that some wave record characteristics be known. For ease of computation, and in consonance with past studies, the mean water level will be considered to be the average of the water-level deviation from a standard baseline (commonly the chart bottom in an analog record) for an entire record (in this study approximately 17-18 minutes). The waves are assumed to approximate a symmetrical distribution about this level. For the purposes of this study, an individual wave is defined as beginning at one upcrossing of the mean water level by the surface of the water, and ending at the next adjacent upcrossing in time.

The procedure for the identification of a wave group is developed from the concepts and interrelationships of the variance, energy, and height parameters of a wave record. The sample variance, V, of a finite length wave record may be determined from the following equation:

$$V = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \qquad (1)$$

where n is the number of equally spaced samples in time, x_i is the water surface elevation at time i, and $\bar{x}$ is the sample mean water level found by

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \, .$$

This study uses the concept that the energy represented in a wave record, the area under a spectral density curve, is proportional to the variance of that record. The energy (average energy per unit area of sea surface) of a simple sinusoidal wave can be written as $E = \rho g H^2/8$, where H is the wave height from crest to trough. If the sea surface is thought of as the sum of an infinite number of small sinusoidal waves, then the total wave energy present may be considered to be the sum of the energies contained in the individual waveforms, which is proportional to the sum of the squares of the heights of those waveforms (Michel, 1968). The variance is then related to the sum of the squares of the wave heights.

This study assumes a Rayleigh distribution of ocean wave heights (Longuet-Higgins, 1952). Its probability density function can be written in terms of the variance, V,

$$p(H) = \frac{H}{V} e^{-H^2/2V} \qquad (2)$$

This distribution describes the frequency of occurrence of wave height H occurring in a finite set of recorded waves. Thus, through the use of the Rayleigh formula, if the variance or energy of the record is known, the distribution of wave heights may be found. Certain height parameters may therefore be found directly from the energy, or variance, of a record using equations of the form $H = k\sqrt{V}$, where k is a constant (Michel, 1968).

The significant height, H_s, the average height of the highest one-third waves, and the corresponding variance will be used herein for the development of a method of defining wave groups. These parameters are related by $H_s = 4\sqrt{V}$.

B. INDIVIDUAL WAVE GROUP DETERMINATION

1. Definition of a Wave Group

Wave groups are noticeable to a casual observer because the heights of the successive waves comprising the group differ from a succession of random wave heights. The short-term variance of a digitized wave record over an interval, such as the time a wave group is present, is thus larger than the variance of the wave record as a whole.

With this concept in mind, individual wave records could be examined by looking through a window of limited duration r to obtain a short sample of the record, as in Figure 1. The variance of this sample, V_i, may then be determined for $t_i = i\Delta t$ by the use of

$$V_i = \frac{1}{n-1} \sum_{j=i-\frac{n}{2}}^{i+\frac{n}{2}} (x_j - \bar{x})^2 \qquad (3)$$

where t_i is the midpoint of the window, Δt is the sampling interval of the record (Δt equals one second for this study), and $\bar{x}$ is the mean of the entire record. The number of samples (n) in the window and its width (r) are related by the equation $r = n\Delta t$. In Figure 1, $a = (i - \frac{n}{2})\ \Delta t$ and $b = (i + \frac{n}{2})\ \Delta t$. The variance is converted into a significant height. This height, H_{SG}, is plotted on a graph according to the midpoint of the window, $(a+b)/2$ (Figure 1). The significant height of the entire observed record, H_{SR}, is also plotted. A height parameter (proportional to the square root of the variance) was used in this study rather than the variance for convenience in graphical scaling and the significant height was chosen as this parameter because of familiarity.

In smoothing a record for wave group characteristics the window is moved through the entire record in time increments corresponding to the sampling rate of the record, and the significant height values plotted. Interconnection of these values, H_{SG}, produces a waveform, called the group waveform, which may then be compared to the value of the significant height of the entire record, H_{SR} (Figure 2). A portion of this new record where the H_{SG} waveform is greater than H_{SR} is a region where the variance over a short time span is greater than the variance of the record as a whole. This region of higher values is considered to identify a wave group.

The term "wave group" implies a series of whole waves, and it can be seen that this region (where $H_{SG} > H_{SR}$) does not necessarily include an integral number of waves, nor do its boundaries coincide with some distinctive part of the observed waveform such as the crest, trough, zero-upcrossing, or zero-downcrossing point. The determination of the wave group boundaries adopted in this study is illustrated in Figure 3. The group waveform computed using a moving time window is seen to intersect the value of H_{SR} at times t_a and t_b, during which $H_{SG} > H_{SR}$. From these times t_a and t_b on the observed wave record, one moves outward from the region of high waves to the first zero-upcrossing encountered. This insures an integral number of waves in the group. The times corresponding to these upcrossings thus mark the beginning and end of the group. In Figure 3, the group begins at time t_A, ends at time t_B, and contains five waves.

2. <u>Selection of Identification Window Width, r</u>

The final step to be taken in applying this method of wave group determination is the selection of a value for r, the width of the window to be used to compute the short-term running significant height (or variance) of the wave record. It was considered desirable that two groups containing waves of identical heights possess identical values of H_{SG}

regardless of the period of the individual waves. The window width should not allow a wave to belong to more than one wave group, and should not allow a single large wave to be identified as a group. The window must also be able to produce a group waveform that will identify two distinctive groups that may be separated by only one wave.

Seventeen-minute wave records with a constant wave period were artificially produced to observe the effects of differing windows on constant period waves. To simulate groups, the amplitudes of selected individual waves were allowed to vary. It was determined by experimentation with these artificially constructed monochromatic wave records that if r is fixed for all records, H_{SG} differences will exist for groups differing only in period. This is to say that two monochromatic wave groups having the same distribution and sequence of wave heights, but differing only in their periods, give different H_{SG} values if the same window is used. However, identical H_{SG} values are obtained if the ratio of the width of the window to the period of the waves in the group remains the same. It was therefore concluded that the window should be dependent upon the period of the waves in the group.

Normally, the average period of the waves in a group occurring in a 17-20 minute record differs from one group to another. Accordingly, it was decided to choose a window equal to or a multiple of the period of the waves in the dominant wave groups, which represent the primary concentration of energy in the record. Since past studies have shown that the average period of the waves that constitute prominent groups closely corresponds to the spectral peak period of the record (Thompson, 1972; Smith, 1974), the width of the window (τ) was determined by the spectral peak period of the wave record T_R.

In order to determine whether to adopt an identification window having a duration equal to the spectral peak period of the record, or some fraction or multiple thereof, a series of experiments using different window lengths was performed using the same artificial records. It was determined that if windows of different duration are used in computing the running short-term significant height in a given record, different H_{SG} values result for the same group. Observing this change in H_{SG}, and since one can expect some deviation of the wave periods in a wave record from the spectral peak period, it was desired to choose a small range of window widths within which the computed values of H_{SG} would not greatly alter the basic shape of the group waveform. The boundaries of the individual groups should not be affected.

Several trials in this study have shown that a small window, one that approximates one wave period or less, may allow the same wave to belong to two groups, which was considered unacceptable. It was also found that with a small window, a single large wave may be identified as a wave group in the group waveform. An advantage with a shorter identification window, however, is that the group waveform is more responsive to period changes in the observed wave record. It was found, on the other hand, that the use of a smoothing window which approximates three wave periods or greater produces a group waveform that is not responsive enough to period changes, and also allows the possibility that two wave groups, which are distinctive to the eye, may be consolidated into one. A wider window may also result in variance values that are very small, and this can eliminate groups of relatively smaller waves.

For this study, the width of the identification window (r) was arbitrarily chosen to approximate twice the spectral peak period (a compromise between extreme windows) to the closest second. As may be seen in Figure 4, the average of the differences between H_{SG} and H_{SR} for five selected wave groups decreases nearly linearly for windows 1 1/2 to 2 1/2 times the peak period. Figure 4 presents characteristics of an artificial wave record, but analysis of actual records shows similar results. Some groups show linear trends of average $H_{SG}-H_{SR}$ for more extreme windows; however, 1 1/2 to 2 1/2 times the peak spectral period appears to be a minimum range of r for linearity. This range avoids the exponential characteristics of narrower windows and the flatter non-responsive wider windows. It was felt that windows approximating twice the peak period would produce a satisfactory group waveform for study.

Two additional restrictions were placed upon the definition of a group. The first is that any positive identification regions ($H_{SG} > H_{SR}$) that are less than one-half the selected identification window length apart will be treated as one group. This restriction was established to prevent the possibility of one wave belonging to two groups. The final restriction is the requirement that a wave group must contain a minimum of two waves.

To summarize, the wave groups in a record are determined by the following steps:

a. Determine the mean water level and variance of the observed waveform.

b. Determine the spectral peak period and select an identification window to approximate twice this value.

c. Operate the identification window upon the observed waveform to produce a short-term variance, or corresponding height parameter. This value (H_{SG} in this study) is plotted at the midpoint of the window, along with the value for the entire record (H_{SR} in this study). The identification window operates from the beginning to the end of the observed waveform (the record), and produces the group waveform.

d. Regions where $H_{SG} > H_{SR}$ denote possible wave groups. Group boundaries are defined by movement outward from the times of intersection of H_{SG} and H_{SR} until a zero-upcrossing is reached in the observed waveform.

e. Positive identification regions must be separated by more than one-half the identification window to be considered separate groups, otherwise a single group is presumed to be present.

f. Groups must contain at least two waves.

Graphical examples of the final product of this method are shown in Figures 5A-5E for records with different spectral peak periods. All of the above steps, including restrictions, were handled by computer using digitized wave data.

III. WAVE RECORD AND WAVE GROUP MEASURES

Various measures of the characteristics of wave records and wave groups were utilized in this study, and these are introduced below. Definitions introduced by previous authors or in common use are used whenever possible.

A. WAVE RECORD MEASURES

1. Spectral Peak Period, T_R

The spectral peak period is the period that represents the primary concentration of energy in the record. The value of T_R is found from the spectral analysis of a record.

2. Variance, V_R, and Significant Height, H_{SR}

The variance of a wave record is determined with the use of Equation (1) and is a measure of the wave energy. This value is used in the determination of the significant height of the record, $H_{SR} = 4\sqrt{V_R}$.

3. Wave Steepness, γ

The wave steepness measure combines the effects of T_R and V_R, and as used here is defined by

$$\gamma = \frac{2\pi}{g} \frac{H_{SR}}{T_R^{\,2}} .$$

B. WAVE GROUP MEASURES

1. Wave Group Duration, D

Wave group duration is the time interval from the beginning to the end of a wave group measured between zero up-crossings, and always includes a whole number of two or more waves. This is illustrated in Figure 6.

2. Number of Waves in a Group, N

N is the number of waves in a group of duration D, and is always an integer of two or more.

3. Wave Group Period, T_G

T_G is the average period of the individual waves that constitute a wave group: $T_G = D/N$.

4. Height of the Largest Individual Wave in a Group, H_{max}

The height of an individual wave is defined as the vertical separation between a crest elevation and the average elevation of the two adjacent troughs. H_{max} is the maximum height occurring in a group, as shown in Figure 6. H_{max} of a group is normalized by use of the ratio H_{max}/H_{SR}.

5. Average Variance Ratio, AVR

A measure to represent the ratio of the average variance of a wave group to the variance of the record as a whole was needed. Its definition and determination can best be described with the aid of Figure 6 and Equation (4). A dimensionless number is formed termed the average variance ratio, AVR. This ratio may be found by squaring and averaging the H_{SG} values from t_A to t_B and relating that to $(H_{SR})^2$, since a height parameter squared differs from the variance by only a constant, and thus is proportional to the energy. Because of ease of graphical presentation of data, a measure related to the AVR, termed $AVR_{\%}$, will be used as shown in Equation (5). $AVR_{\%}$ may be thought of as the percentage by which the average variance of a group, V_G, differs from the variance of the entire record, V_R.

This procedure may be expressed as follows:

$$AVR = \frac{\bar{V}_G}{V_R} = \frac{\frac{1}{k} \sum_{t_A/\Delta t}^{t_B/\Delta t} (H_{SG})_i^2}{(H_{SR})^2}, \text{ where } k = \frac{t_B - t_A}{\Delta t} \qquad (4)$$

$$AVR_{\%} = \frac{\bar{V}_G - V_R}{V_R} \times 100 = (AVR-1) \times 100 \qquad (5)$$

IV. WAVE DATA SELECTION

The wave records used in this study were obtained from the Coastal Engineering Data Network (CEDN) sponsored by the California Department of Navigation and Ocean Development and the University of California Sea Grant Program. Scripps Institution of Oceanography provides overall direction for the program. Four network stations in Southern California were utilized and their locations are shown in Figure 7.

Wave records were obtained with bottom-mounted pressure sensors placed at depths of approximately 10 meters. The sensors do not possess high-pass filters and therefore record all long waves present, including the astronomical tides. These long-term sea-level variations were considered to be a second-order effect when compared with the wave heights occurring and were neglected in this study. Wave data from these sensors are digitized by CEDN on magnetic tape at a sampling rate of one second, and are calibrated in units of pressure (cm of water). Each individual record was of approximately 17-minutes duration (records range from 1024 to 1078 seconds) with a record generally taken every 10 hours at each station.

CEDN produces a spectral analysis of the pressure record, corrected for hydrodynamic damping, and publishes both graphical representations (Figure 8) and tabular values (Figure 9) of the energy spectra for each station by months. The wave records used for wave group analysis in this study, selected from these CEDN presentations, were chosen for the display of sharp unimodel spectra. Individual records were selected when greater than 30% of the energy occurred in one CEDN period band. The 30% limit was arbitrarily chosen for the purpose of insuring that a prominent spectral peak existed within the record. The spectral peak period used in the determination of the identification window width was chosen by interpolation of the CEDN tabular data to the nearest whole second.

Computations of variance, in this study, were derived from the pressure records provided by CEDN and were not modified for hydrodynamic damping. It was assumed that the dominant period determined from spectral analysis by CEDN would closely correspond to the dominant period of the pressure waveform over the range of periods dealt with (7 to 20 seconds).

Two hundred eight records were selected to be examined, which resulted in the identification of 1643 individual wave groups. The height-period characteristics of these records are shown in Figure 10. The graph also contains steepness curves, where wave steepness is defined by

$$\gamma = \frac{H}{L} = \frac{2\pi}{g} \frac{H_{SR}}{T_R^{\,2}} ,$$

where H_{SR} is the significant height and T_R is the spectral peak period. The steepness of rapidly growing and fully arisen seas in the range of periods dealt with in this study is greater than or equal to 0.02 according to wave forecasting graphs (Bretschneider, 1958). Accordingly, the wave records examined, when corrected for hydrodynamic damping, cover a wide range of steepnesses, from fully arisen seas to old swell.

V. ANALYSIS AND INTERPRETATION OF WAVE DATA

Each record was examined for relationships between the group and record measures defined in Section III, and for interrelationships between the group measures themselves.

Since values of V_R and T_R can cover a wide range, these record measures were grouped into categories of variance and period for statistical handling. The records were first divided into five variance bands as shown in Figure 11. Records with H_{SR} greater than one standard deviation from the mean significant height of all the records are included in bands where the variance is less than 200 cm^2 or greater than 700 cm^2. The remainder of the records were divided into three variance bands: 250 to 350 cm^2, 400 to 500 cm^2, and 550 to 650 cm^2. A 50 cm^2 separation was used to isolate the five bands from each other. These five intervals are equivalent to significant height intervals of less than 57 cm, 63 to 75 cm, 80 to 89 cm, 94 to 102 cm, and greater than 106 cm respectively.

Spectral analysis of the wave records performed by CEDN yields $1/T_R$ to an accuracy of $\Delta f = \pm 0.0034$ Hz; thus, over the range of wave periods of interest, 7 to 20 seconds, the precision with which the periods can be obtained is approximately $\pm$ 0.17 sec and $\pm$ 1.4 sec, respectively. It would be desirable to examine the relationship of discrete values of T_R with, or incorporated in, other parameters (e.g., γ or T_G/T_R), but because of the low precision with which T_R is known (especially at longer periods) it was decided to deal with bands of T_R. The bands were chosen to follow the CEDN produced period bands, which include the lower limit of the band, but not the upper limit. The distribution of records with respect to these period bands is shown in Figure 12. T_R period bands less than six seconds were not examined because of the effect of extreme hydrodynamic damping. There was found to be insufficient data available in the 10-12 second period band for statistical treatment, and this band is omitted. The 6-8 second band and the 8-10 second band were combined because of sparsity of data.

A. RELATIONSHIPS OF GROUP MEASURES TO RECORD MEASURES

1. Average Wave Group Period, T_G

Figure 13 shows cumulative distributions (in percentage of groups) of the average period of wave groups occurring in records having spectral peak periods falling in the five indicated bands. It appears that more groups have periods falling within the spectral peak period band than in any of the adjacent bands. However, a wide spread of group periods is apparent, such that the longer spectral peak period bands do not possess a majority of the total groups. The spread may be caused by individual groups of shorter periodicity produced toward the short-period tail of the frequency spectrum, and possibly also by the presence of secondary wave trains.

An upper cutoff in the distribution is evident for each spectral peak period band. This cutoff closely corresponds to the upper limit of the associated peak period band. This agrees with the dispersion concept in which waves of longer periods travel with greater celerity, and thus groups of these longer periods have already passed the wave gage. The distributions shown in the figure appear to contradict observations by other investigators (Thompson, 1972; Smith, 1974) that the average group period is equal to the period of maximum energy density. An explanation may lie in the selectivity of the groups, in that the method used in this study may identify groups that were not significant to previous investigators.

The relationship between T_G and the variance of the wave record was not examined because a wide range of combinations of height and period are possible in ocean swell.

2. <u>Number of Waves in a Group, N</u>

The number of waves in a group is shown in the cumulative percentage curve of Figure 14 representing the 208 wave records examined. The figure shows that the modal number of waves per group is 4 or 5, and that 10% of the wave groups have 9 or more waves. The maximum number of waves in a group was found to be 26.

Wave records with similar peak period bands were separated, and the cumulative distribution for N for each band shown in Figure 15. The distributions of N for each period band are statistically similar, which indicates that there is little dependence of N upon the peak period. There is a slight tendency for longer period bands to have a greater percentage of wave groups of larger N.

The number of waves per group as a function of the selected variance bands is shown in cumulative-distribution form in Figure 16. As may be seen, there appears to be even less variability in the frequency distribution of N with variance than there is with spectral peak period. It is concluded, therefore, that the number of waves in a group is essentially independent of both the dominant period and the energy content of a wave record.

3. <u>Amount of Time Wave Groups are Present, ΣD</u>

The cumulative time during which wave groups are present in a record, ΣD, equals the combined duration of the wave groups, given by

$$\Sigma D = \sum_{i=1}^{n} (N \cdot T_G)_i ,$$

where n is the number of wave groups, including groups truncated by the ends of the record. The cumulative distribution of ΣD is shown in Figure 17; the average duration of the analyzed wave records is approximately 1075 seconds. An average time of group occurrence was found to approximate one-half the record length, with a maximum deviation of about $\pm$ 200 seconds.

It is speculated that the amount of time groups are present does not depend upon the variance of the record, since

N and T_G are not dependent upon the variance. With regard to the relationship of ΣD to the spectral peak period, if T_R were to increase, longer T_G would be possible and this would tend to increase the duration of the individual groups. However, an increase in T_R would tend to reduce the number of waves possible in a 17-minute record, and therefore the number of groups possible. It thus appears that a relative balance occurs between the individual group duration and the number of groups per record such that a change in T_R would be expected to have little effect upon ΣD.

4. <u>Average Variance Ratio Percentage, $AVR_{\%}$</u>

As stated above, $AVR_{\%}$ is a measure of the energy in an individual wave group relative to the energy in the record; positive/negative values indicate that the wave group has more/less energy than the wave record. The distribution of $AVR_{\%}$ for all 1643 groups identified is shown in Figure 18. It is seen that approximately 84% of the groups have an energy level greater than the record as a whole.

The groups were once again separated into peak period bands, and the distribution of $AVR_{\%}$ by these bands is shown in Figure 19. It may be seen that the $AVR_{\%}$ distributions are similar, indicating that $AVR_{\%}$ is independent of the spectral peak period of the record.

Figure 20, on the other hand, shows a distinctive relationship between the $AVR_{\%}$ occurrence and the variance of the wave record. It may be seen that the greater the value of V_R, the more heavily weighted the distribution of groups is toward higher $AVR_{\%}$ values. Stated in more practical terms, the greater energy a wave train possesses, the greater is the possibility that individual wave groups will have proportionately higher energy.

5. Maximum Wave Height in a Group, H_{max}

The value of H_{max}, the single highest wave in a group, may be expected to be statistically dependent upon the variance of the record from consideration of the Rayleigh distribution applied to ocean waves. Thus, as variance increases the probable maximum height obtainable in the record should be expected to increase with the square root of the variance. This relationship is generally indicated in Figure 21 for the upper and lower limits of the distribution. A change in the spectral peak period for the same number of waves would not be expected to affect the H_{max} values if the energy level remained the same in the record. This is inferred from theoretical considerations and is not presented graphically.

B. INTERRELATIONSHIPS OF GROUP MEASURES

An examination of the six possible interrelationships of the four group measures $AVR_{\%}$, T_G, N, and H_{max} was conducted. The principal observations follow.

1. $AVR_{\%}$ and T_G

Figures 22-26 depict the relationship of $AVR_{\%}$ to the average group period for the spectral peak period bands indicated. It appears that the higher values of $AVR_{\%}$ generally coincide with the groups whose T_G approaches the spectral peak period. The figures also show a relatively sharp period cutoff at the upper end of the spectral peak period band, above which few groups and low $AVR_{\%}$ values occur.

2. $\underline{AVR_{\%}}$ and N

Figures 27-33 show the relative distribution of $AVR_{\%}$ as a function of the number of groups for a constant N. It may be seen that as the number of waves in a group increases, the distribution migrates toward higher $AVR_{\%}$ values and becomes less peaked.

It has been shown that $AVR_{\%}$ is highly dependent upon the variance (Figure 20); for an increase in variance there must be a corresponding increase in the percentage of groups with high $AVR_{\%}$. This redistribution of groups with respect to $AVR_{\%}$ must occur with no change in the distribution with respect to N, since it has also been shown that N appears to be independent of the variance (Figure 16). This is evidently accomplished by the shifting of groups having a particular N to higher $AVR_{\%}$ values within the ranges of $AVR_{\%}$ implied by Figures 27-33. This is illustrated by comparison of the distributions shown in Figures 34 and 35 for the extreme variance bands ($V_R < 200$ cm^2 and $V_R > 700$ cm^2). The figures give the approximate percentage of groups in a number of $AVR_{\%}$ bands, and show that for an increase in the total energy of a record, a much wider range of relative wave group energy ($AVR_{\%}$) is possible. It may also be noted that there are apparent limits to $AVR_{\%}$ for each individual value of N.

3. $\underline{AVR_{\%} \text{ and } H_{max}/H_{SR}}$

This relationship is shown in Figure 36. Separated bands of $AVR_{\%}$ (-0.25 to 0, 0.50 to 0.75, 1.00 to 1.25, 2.00 to 2.25, and > 3.00) were chosen to emphasize the vertical spread and trend in H_{max}/H_{SR} as $AVR_{\%}$ increases. The figure shows that groups with large $AVR_{\%}$ are more likely to have an extreme H_{max} than groups with small $AVR_{\%}$. In addition, a particular value of H_{max}/H_{SR} cannot be used as a measure of the relative energy in a group, but may suggest a minimum energy level possible. It may also be noted that the maximum height in a group may be less than the significant height of the record; the figure shows that H_{max} is dominantly less than H_{SR} for $AVR_{\%}$ values less than 1.00, but greater than H_{SR} for $AVR_{\%}$ values of 2.00 or greater.

4. N and T_G

Figures 37-41 show a general trend that the number of waves in a group will probably be greater when the average period of the group approaches the spectral peak period of the record. This is a comfortable conclusion since the farther away the average period of a group is from the spectral peak period, the fewer are the number of waves that would be anticipated from wave interference considerations. Wave groups with average group periods greater than the spectral peak period band are once again seen to be few in number and have small N.

5. N and H_{max}/H_{SR}

The more waves in an individual wave group, the greater is the chance of obtaining an extreme wave height. This is shown in Figure 42. For a given N, there is an apparent lower limit to the value of H_{max}/H_{SR}, and for a given H_{max}/H_{SR} a wide range of N is possible. It may also be noted that for groups with 12 or more waves, the maximum height in the group is likely to be greater than the significant height of the record.

6. <u>T_G and H_{max}/H_{SR}</u>

The final interrelationship was examined without the aid of a figure. H_{max}/H_{SR} was shown to increase with large $AVR_{\%}$ (Figure 36) and large N (Figure 42). However, $AVR_{\%}$ and N were shown to be independent of the spectral peak period (Figures 19 and 15), but dependent upon how closely the average group period approximates the spectral peak period (Figures 22-26 and Figures 37-41). Therefore, extreme relative wave heights (i.e., large values of H_{max}/H_{SR}) should be expected when the group period approaches the spectral peak period, regardless of the value the spectral peak period assumes.

C. OTHER RELATIONSHIPS

In order to determine how wave-group properties vary over the life of an arriving swell train, a time-series examination was made of 12 synoptic swell trains, each sampled by a 17-minute record at approximately 10-hour intervals. Each train was selected on the basis of displaying a well-defined wave height maxima and a systematic decrease of T_R with time. It was found that as the wave-record measures of a synoptic wave train change, the associated wave-group properties change in a manner that would be expected from consideration of the analysis described above. The presentation of this work is not included since no additional information concerning wave-group properties was revealed.

A comparison of records with respect to the four different wave gage sites likewise resulted in the conclusion that wave-group relationships are independent of location. Differences in degree and direction of site exposure to open ocean wave conditions resulted mainly in wave steepness differences, which influence wave groups only as the height parameter changes.

VI. SUMMARY

A method of digitally analyzing an ocean wave record for wave-group characteristics with the use of a moving group identification window was developed. The window was chosen to be dependent upon the spectral peak period of the record. The short-term variance of the record within this moving window was compared to the variance of the entire record to identify intervals of apparent energy concentration. These intervals were considered to be related to the occurrence of wave groups.

Two hundred eight wave records that exhibited unimodel spectra were selected for analysis. The recording sites were four stations on the Southern California coast that are part of the Coastal Engineering Data Network system of the State of California. Wave record measures (the spectral peak period and the variance), as well as wave group measures (the average group period, the number of waves, the maximum wave height, and the relative group energy) were defined, determined by computer analysis, and then related to one another.

It was found that the number of waves in a group is independent of both the spectral peak period and the variance of the wave record. However, the amount of energy contained in wave groups relative to that in the record increases as the total energy of the record increases. Also, average group periods of greater than the spectral peak period are unlikely to occur, but group periods less than the peak period are not uncommon. Both an increase in group energy relative to the wave record and also in the number of waves in a group increase the possibility of obtaining an extreme wave height in a group relative to the significant height of the record. Further, the closer that the average wave group period approximates the spectral peak period of the record, the higher is the relative energy and number of waves possible in the group. Further study of this relationship is extremely desirable since it is evident that all wave group characteristics are dependent upon it.

In view of these findings, it would therefore be expected that in a synoptic wave train the largest ratio of group to record energy, the largest ratio of maximum wave height within a group to significant height of the record, and the largest number of waves in a group would occur at the time of peak energy arrival. This conclusion may be expected to apply regardless of the spectral peak period.

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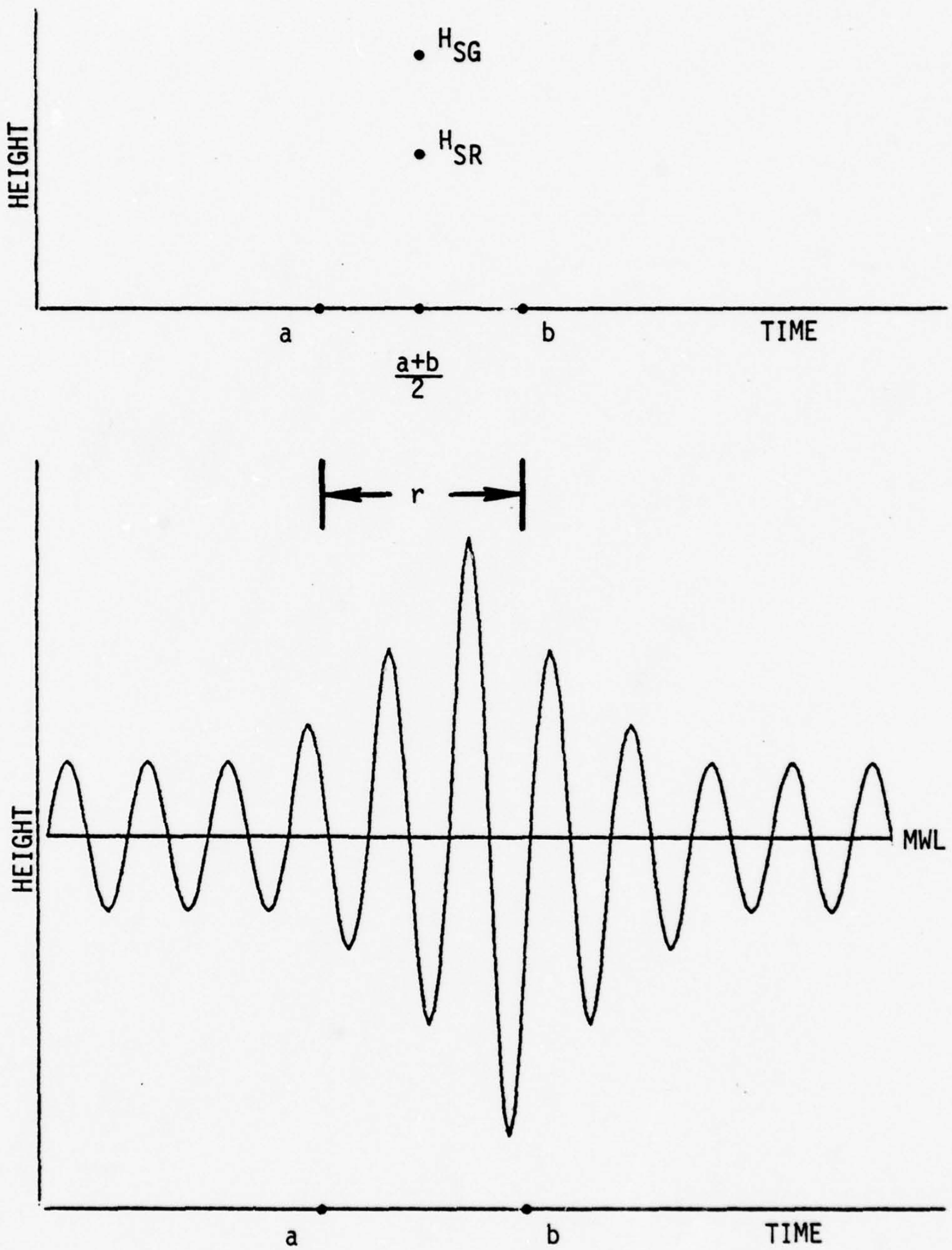

Figure 1. Example of r, H_{SG}, and H_{SR}.

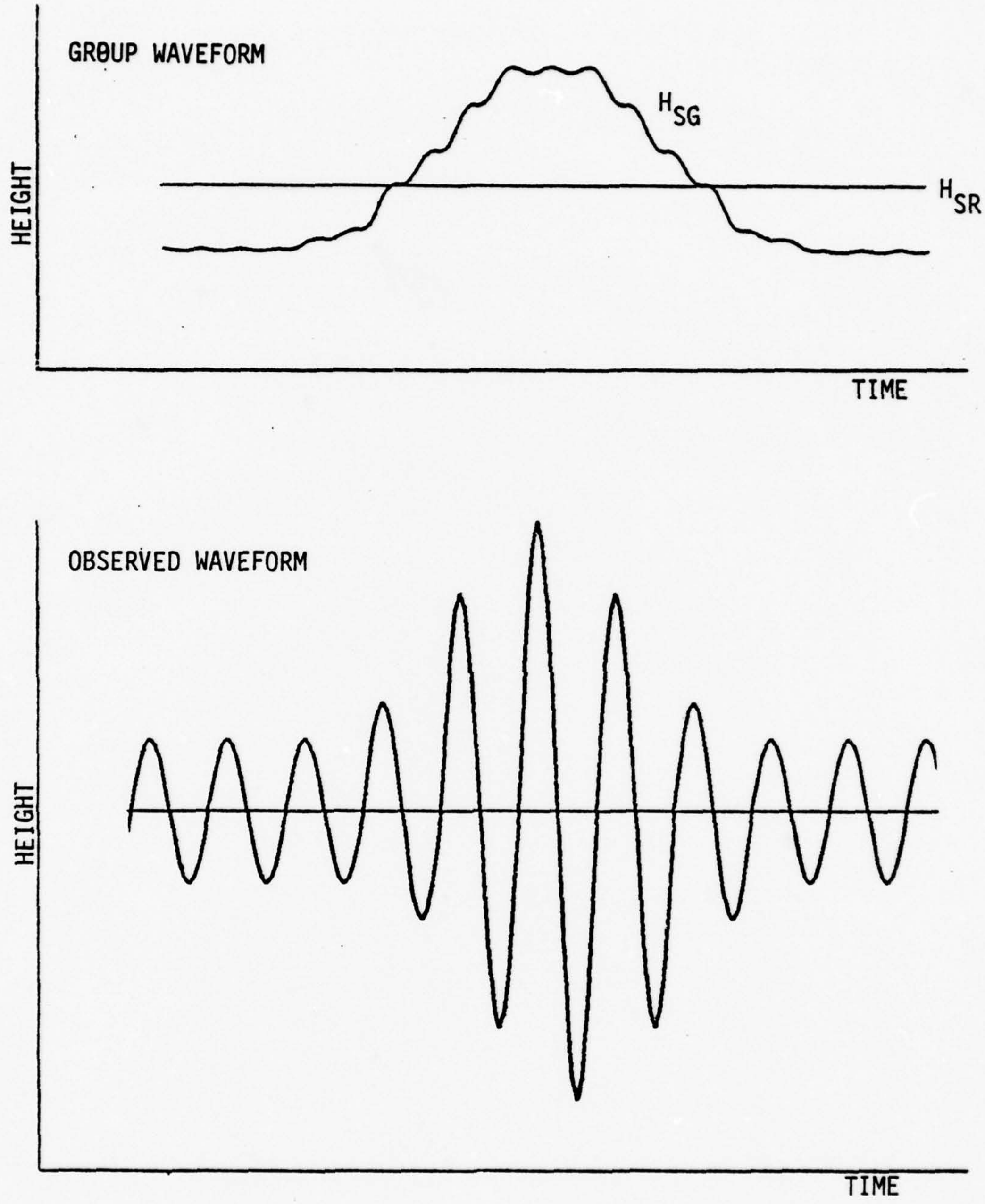

Figure 2. Group Waveform in Relation to Observed Waveform.

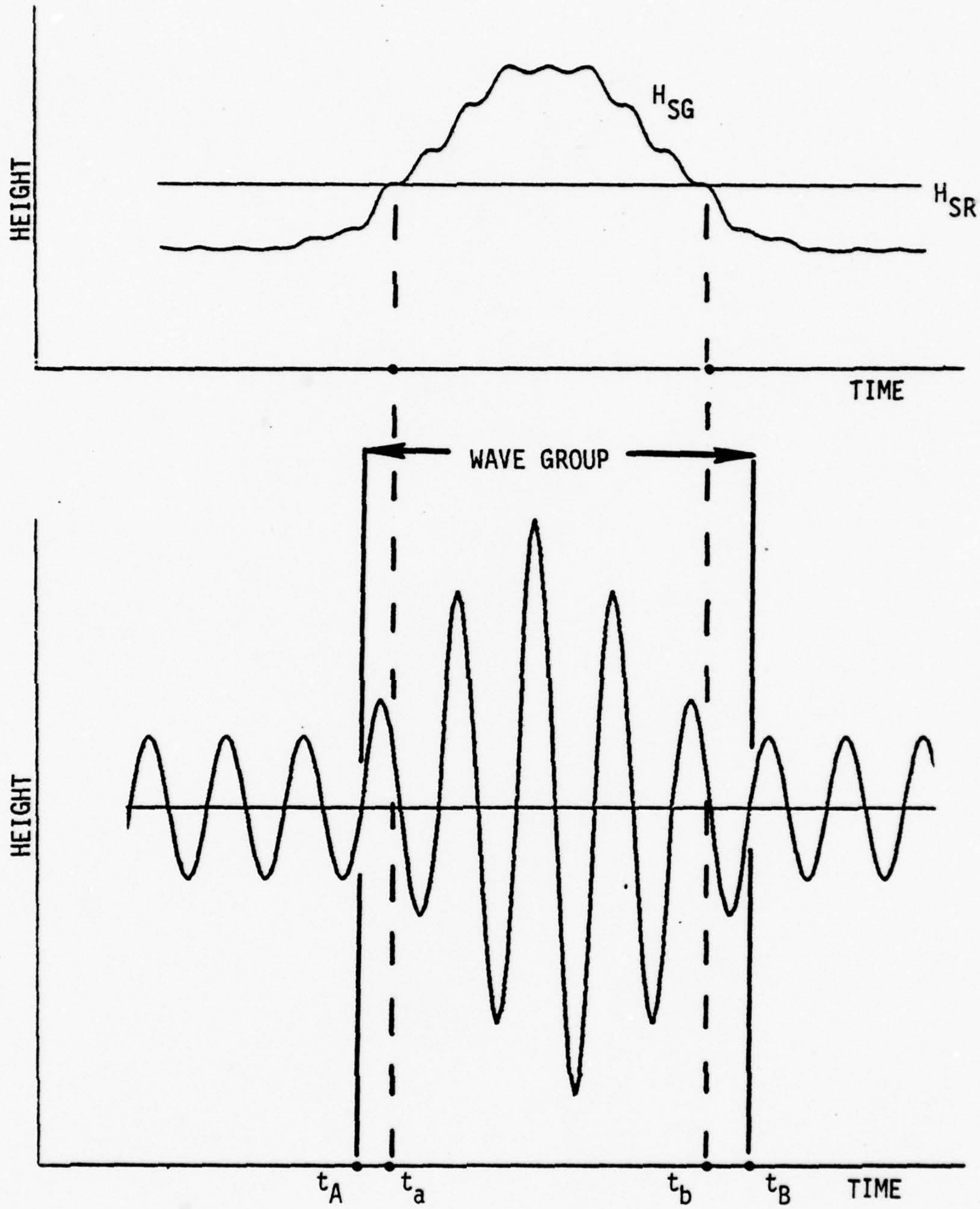

Figure 3. Determination of Wave Group Boundaries.

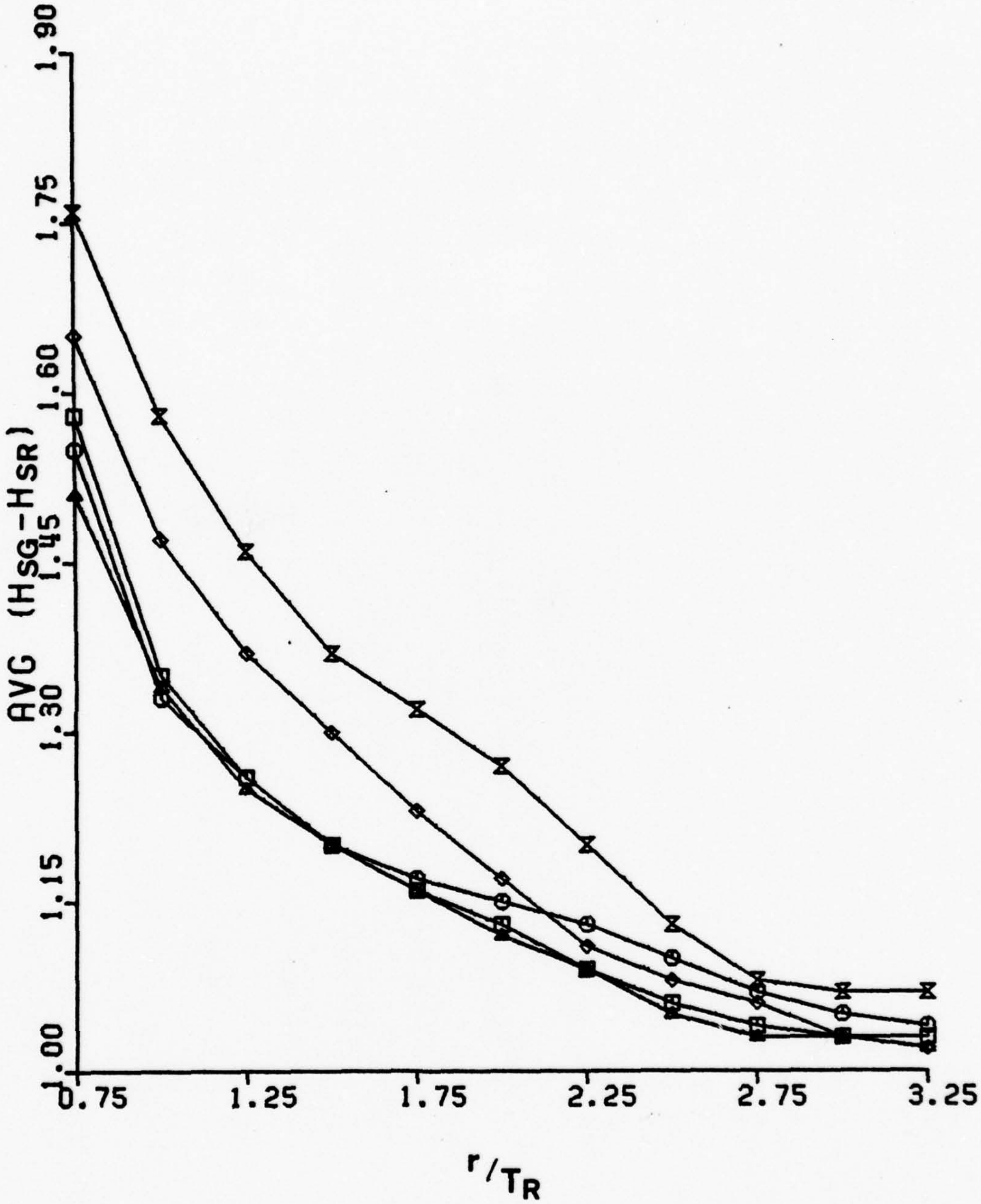

Figure 4. Average Differences in H_{SG} and H_{SR} as a function of Window Width (5 selected wave groups).

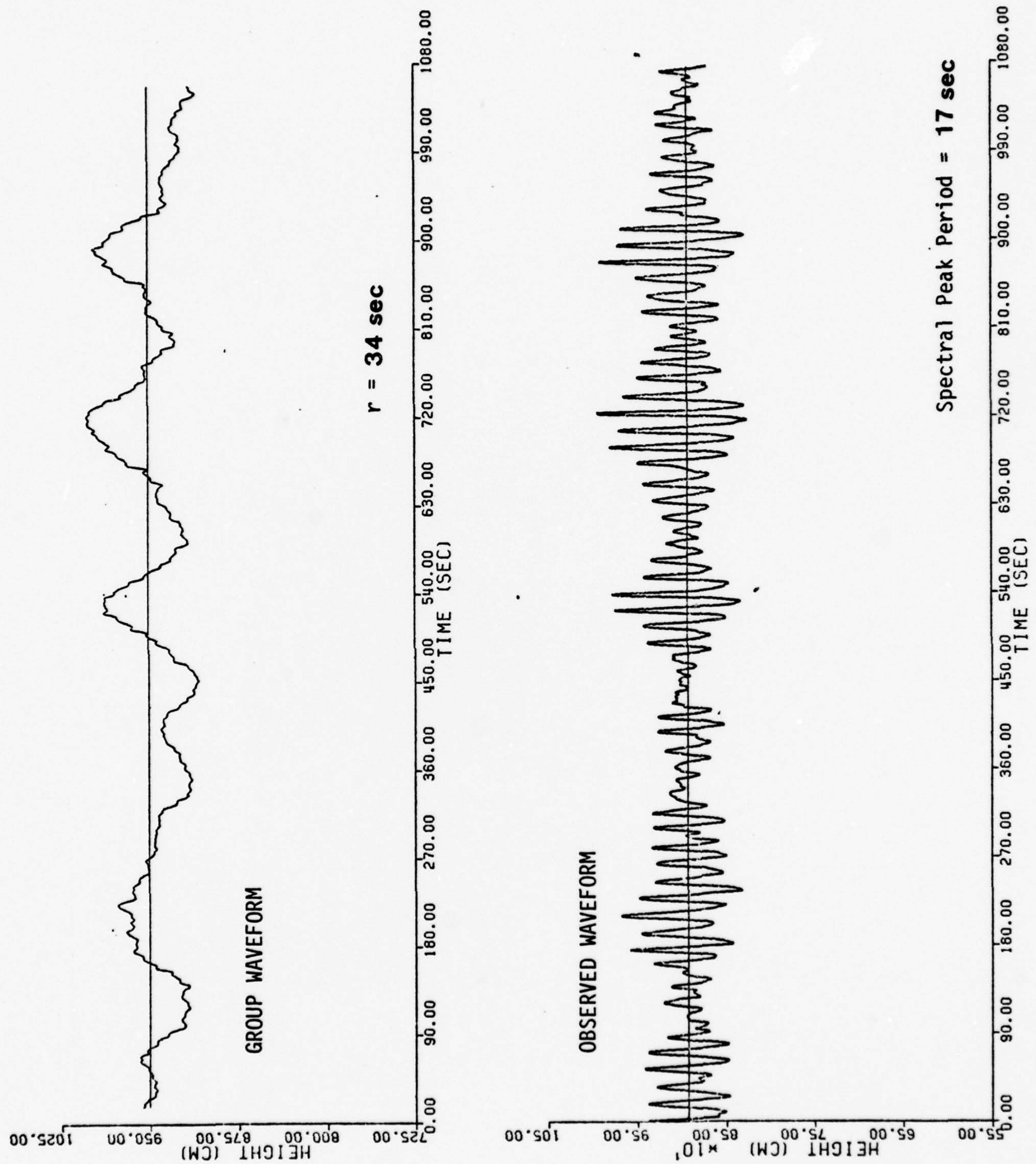

Figure 5A. Example of Group Waveform Analysis.

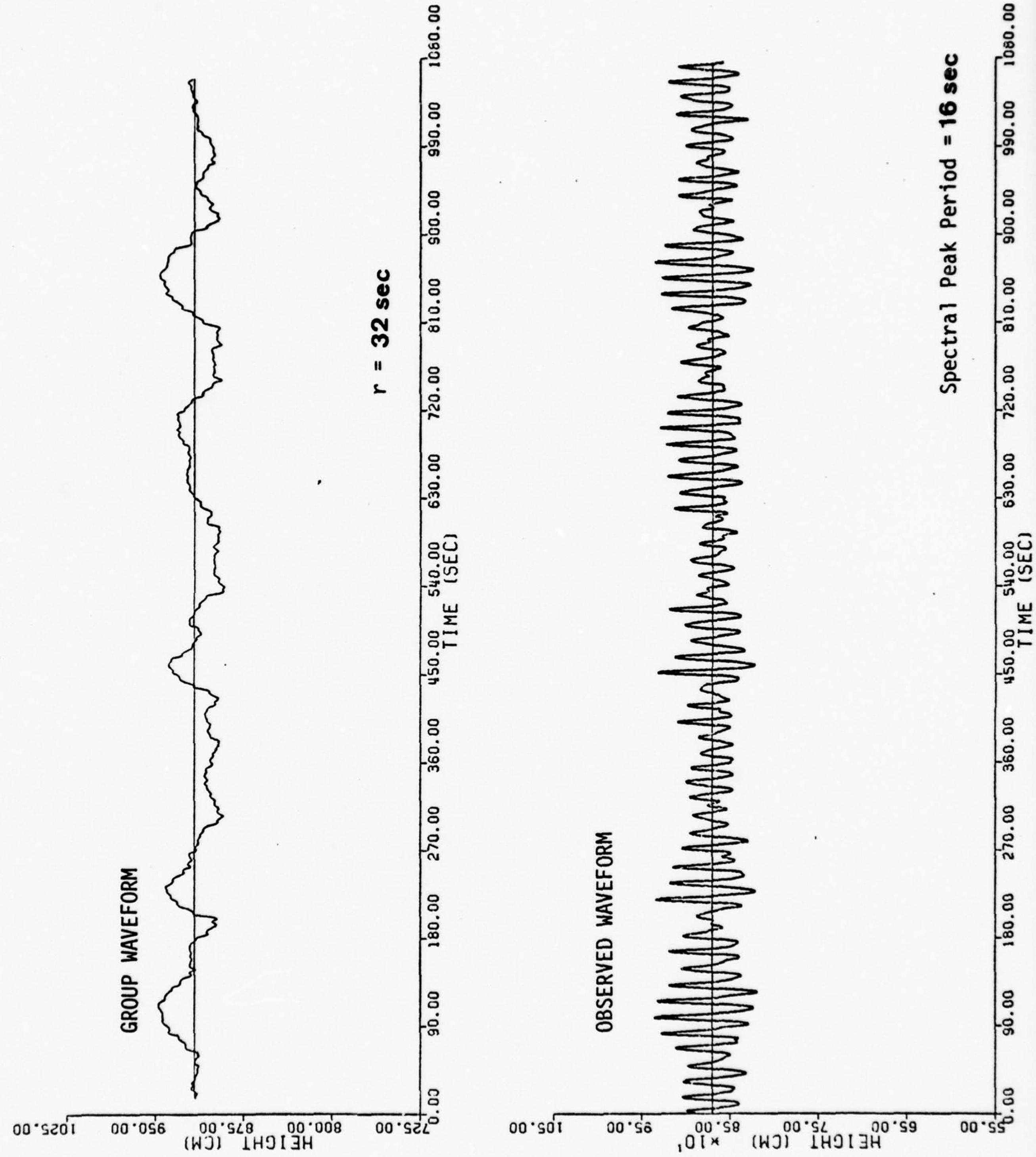

Figure 5B. Example of Group Waveform Analysis.

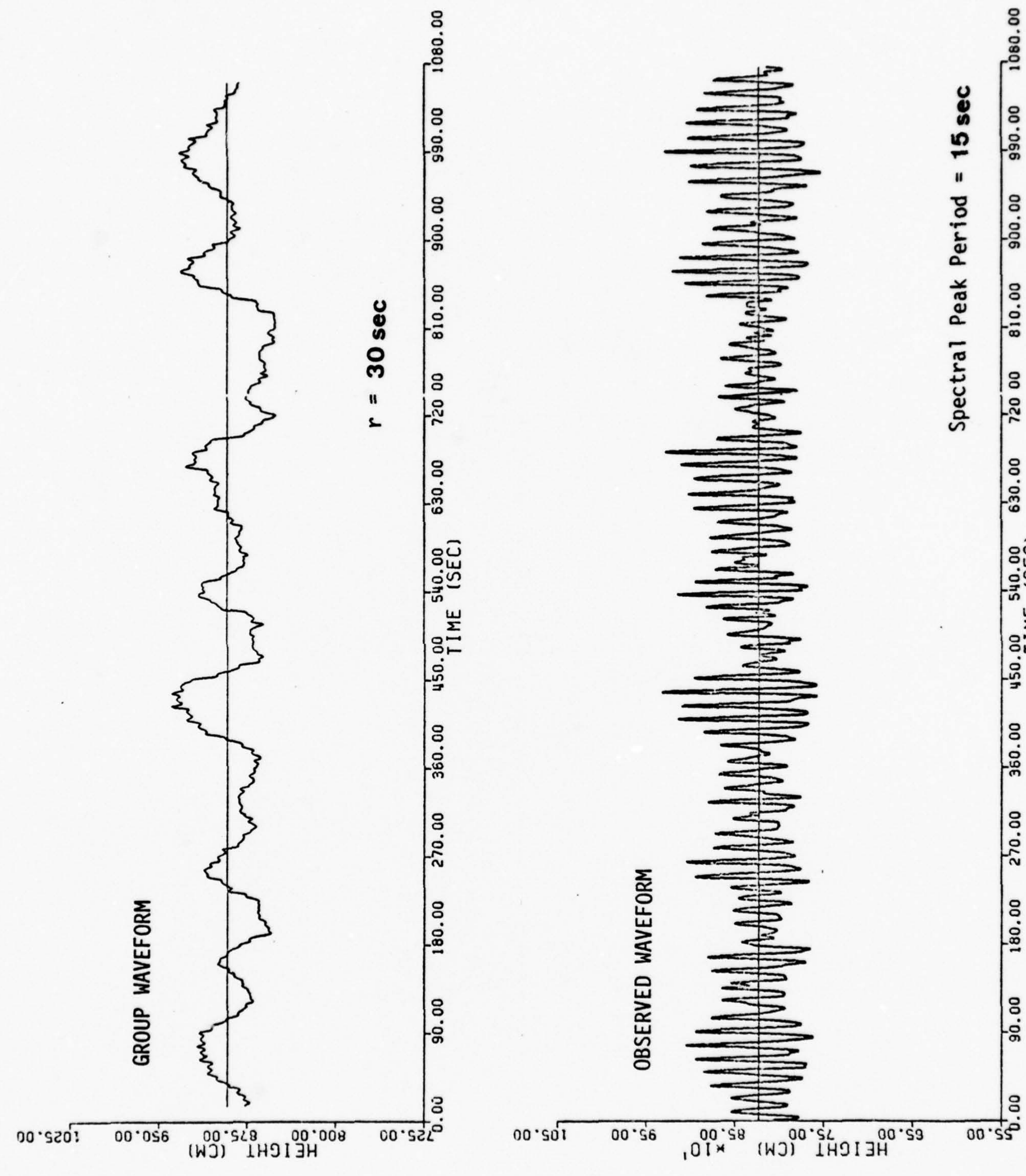

Figure 5C. Example of Group Waveform Analysis.

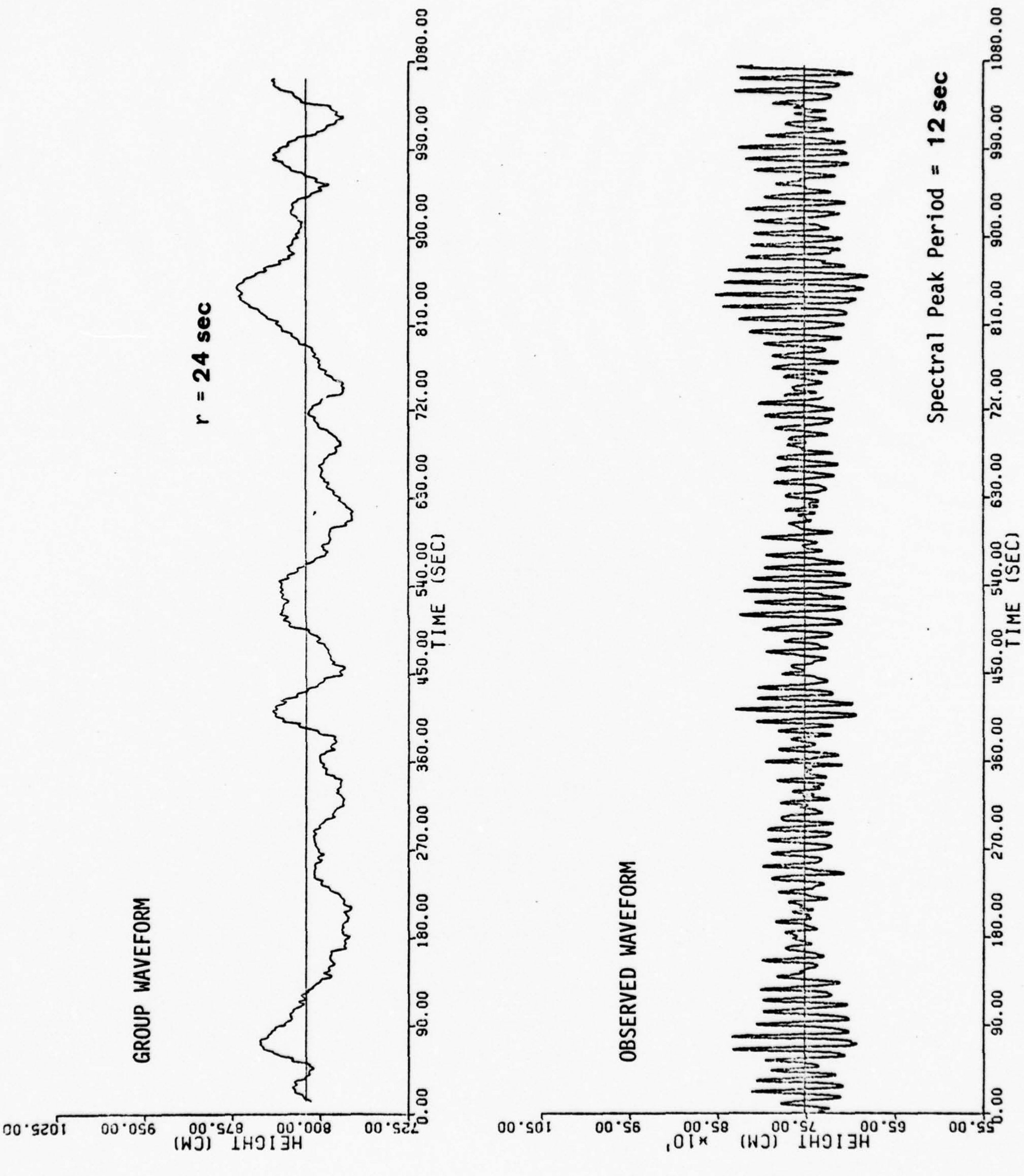

Figure 5D. Example of Group Waveform Analysis.

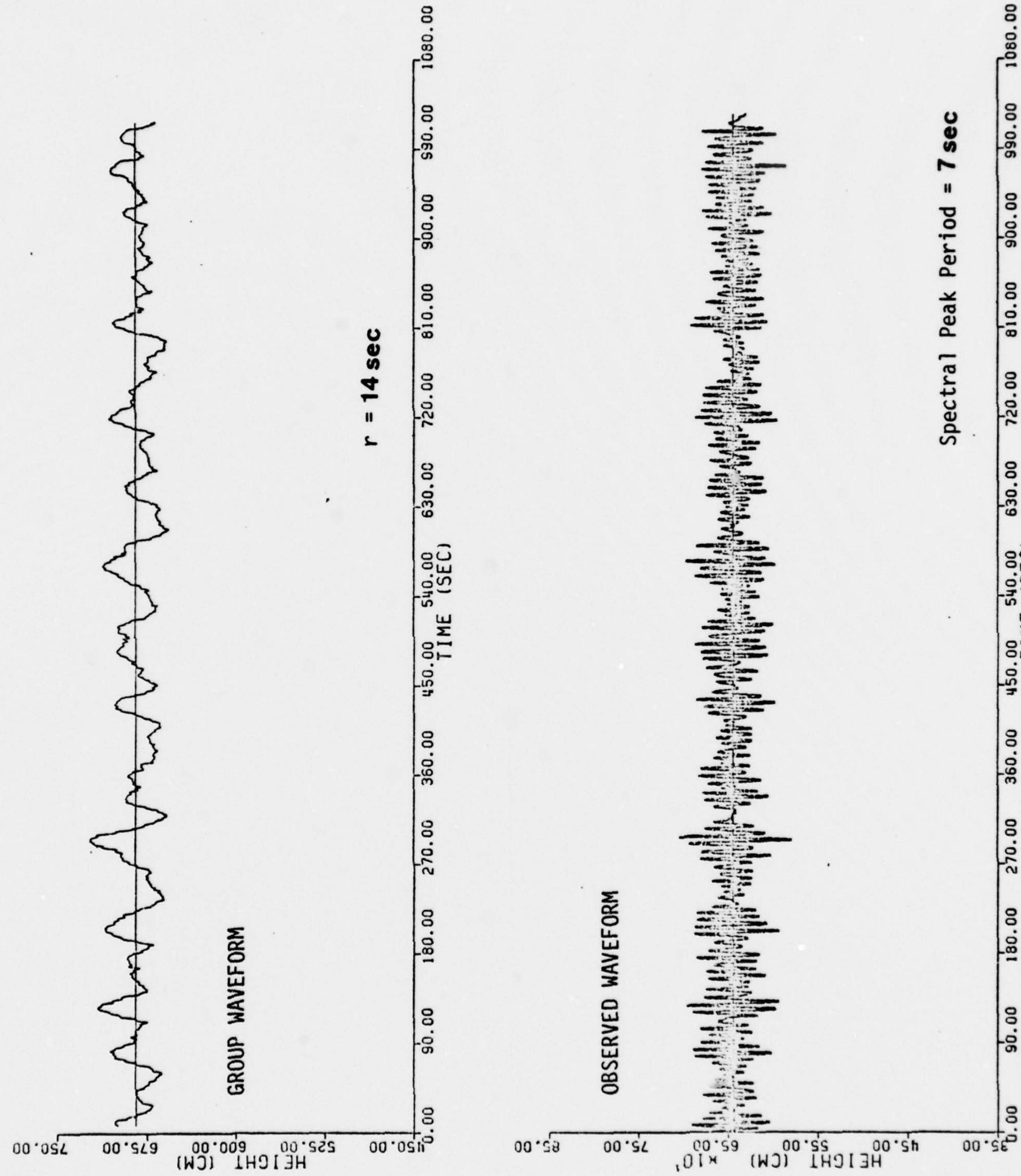

Figure 5E. Example of Group Waveform Analysis.

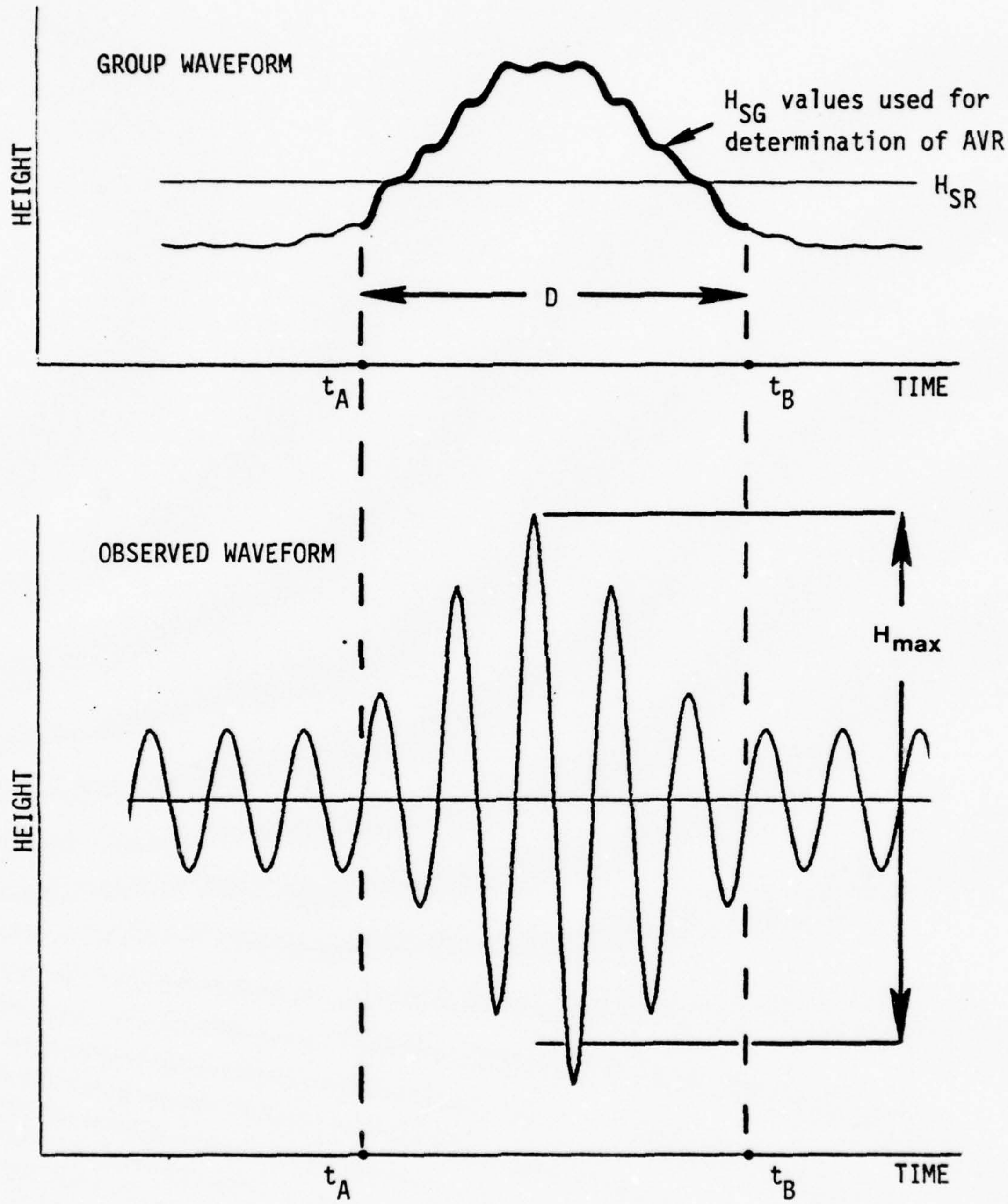

Figure 6. Determination of AVR and H_{max}.

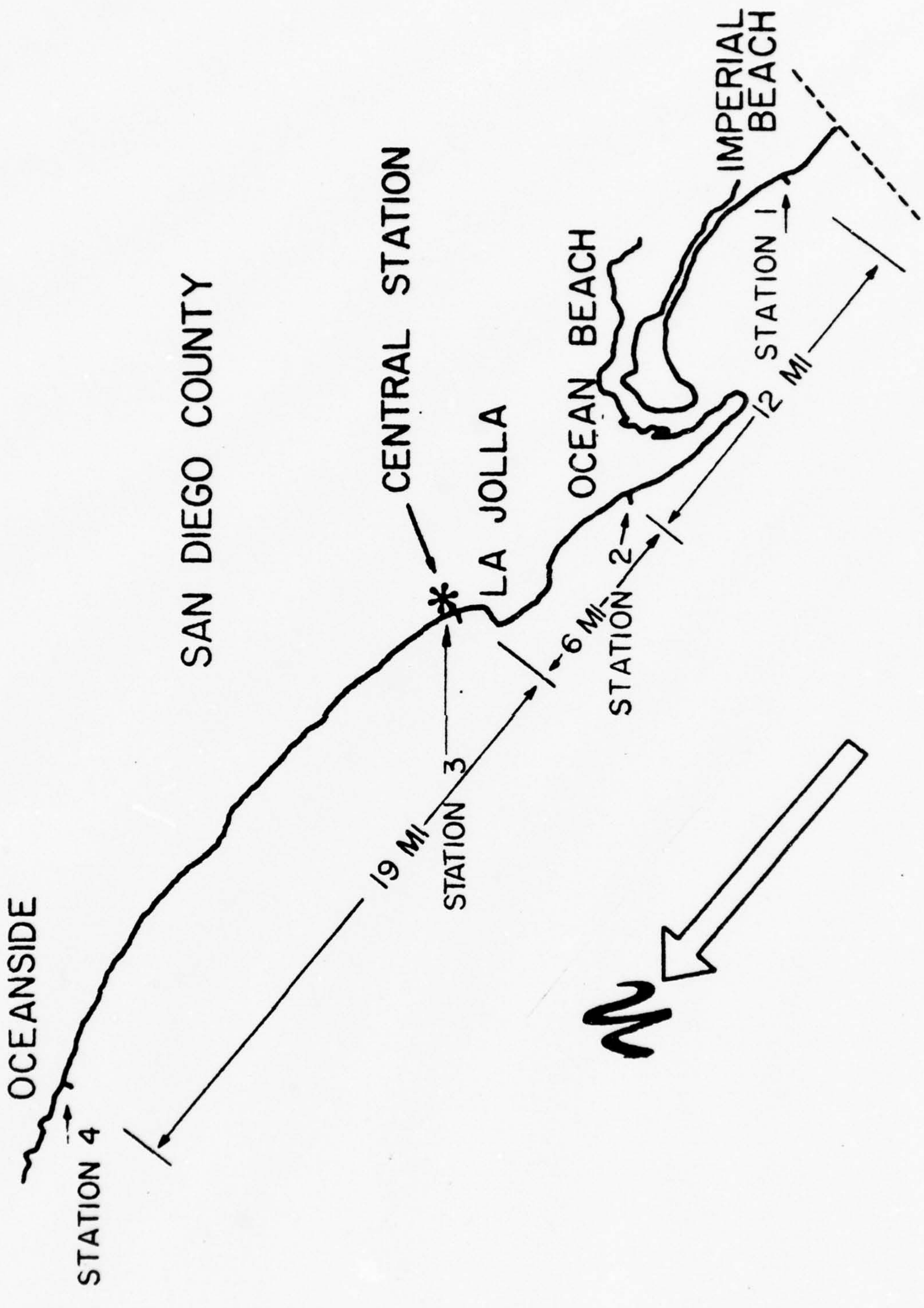

Figure 7. Location of CEDN Stations (from Seymour, et al, 1977).

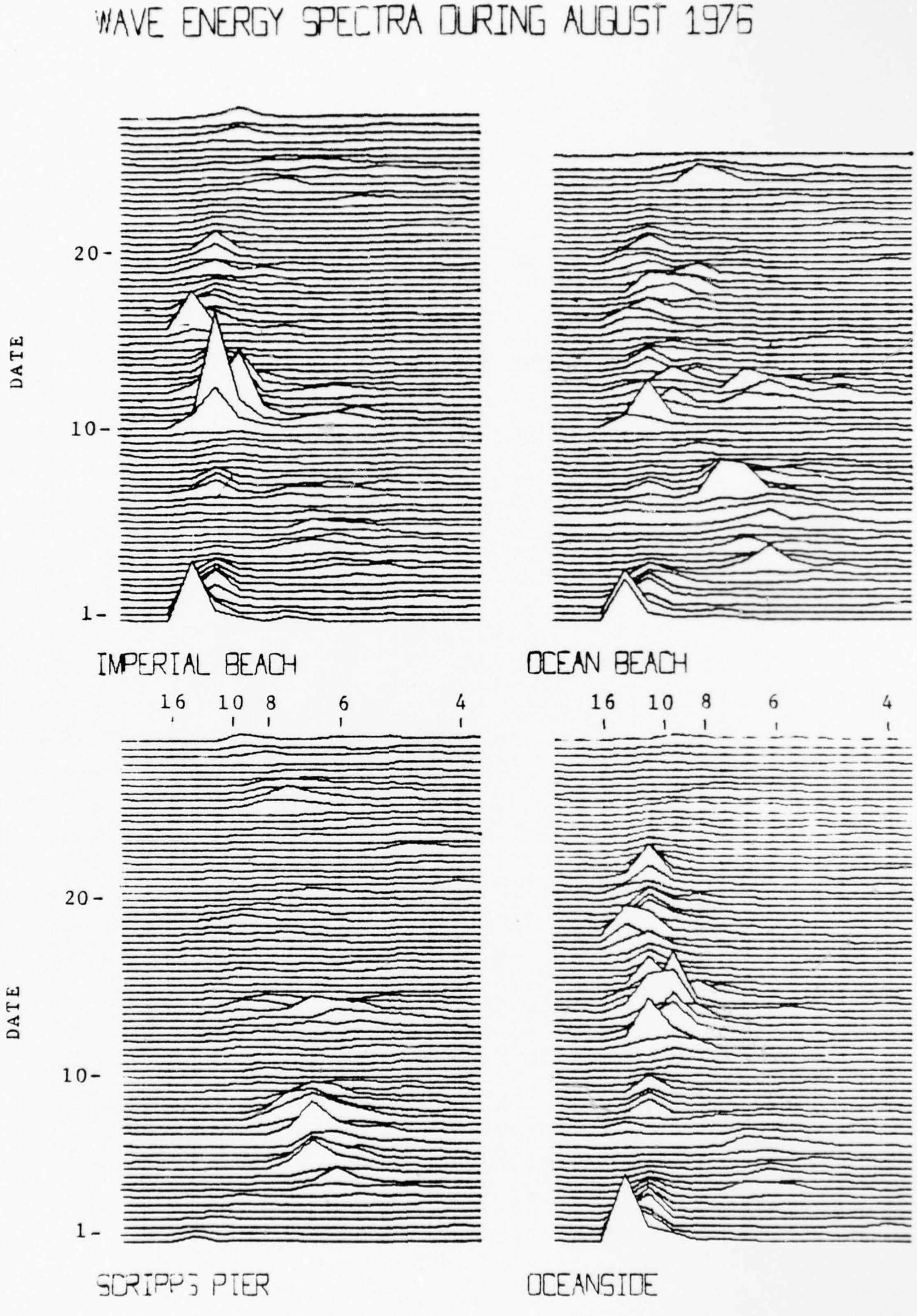

Figure 8. Graphical Presentation of CEDN Spectra (from Seymour, et al, 1977).

PERCENT ENERGY IN BAND
(TOTAL ENERGY INCLUDES RANGE 2048-4 SECS)

BAND PERIOD LIMITS (IN SECS)

22+	22-18	18-16	16-14	14-12	12-10	10-8	8-6	6-4
2.6	6.1	53.6	6.5	6.6	5.5	9.8	5.2	4.1
2.2	6.1	48.0	10.3	3.8	3.6	13.5	8.4	4.1
2.4	3.4	57.9	12.7	4.8	3.9	8.2	3.6	3.2
3.2	3.6	42.3	24.1	4.8	2.3	11.2	4.8	3.7
1.6	1.4	20.0	25.6	8.2	5.1	5.2	6.7	26.3
1.3	0.8	21.9	37.5	7.1	2.2	5.5	8.1	15.7
3.5	0.5	21.1	23.0	25.0	2.0	6.4	4.2	14.3
2.0	0.4	7.2	42.4	16.2	8.5	3.5	7.5	12.3
1.0	0.4	1.2	15.5	21.5	16.9	3.8	5.3	34.5
1.4	0.1	1.7	18.1	15.7	11.4	3.8	19.3	28.5
0.7	0.1	0.7	4.3	4.6	3.2	4.0	55.3	27.2
1.4	0.2	0.8	7.6	5.4	3.3	4.9	44.7	31.7
2.8	0.3	0.5	2.8	7.1	1.9	11.4	32.0	41.1
1.3	0.2	0.4	2.2	3.5	1.9	8.4	41.1	40.9
1.2	0.4	0.3	1.7	3.3	2.6	10.4	35.2	44.9
1.5	0.4	0.3	1.0	1.9	1.3	14.3	40.0	39.2
2.7	1.0	1.5	0.7	1.3	0.8	5.2	44.0	42.8
2.6	1.3	2.4	0.5	1.1	1.1	7.3	48.9	34.9
1.4	1.7	3.5	0.6	1.5	0.8	9.6	45.6	34.3
1.2	0.9	7.6	1.9	0.8	2.5	14.1	39.0	31.9
2.0	0.2	0.5	3.8	0.7	1.6	33.5	40.3	17.5
1.3	0.3	3.0	12.7	1.5	1.7	20.0	37.0	22.6
1.1	0.2	1.3	6.8	1.5	2.4	27.2	31.1	28.3
2.5	0.1	0.5	2.7	4.7	2.2	29.0	30.0	29.3
1.7	0.3	0.9	7.2	5.5	3.3	18.2	23.1	39.9

Figure 9. Tabular Presentation of CEDN Spectra, Ocean Beach, August 1-9, 1976 (from Seymour, et al, 1977).

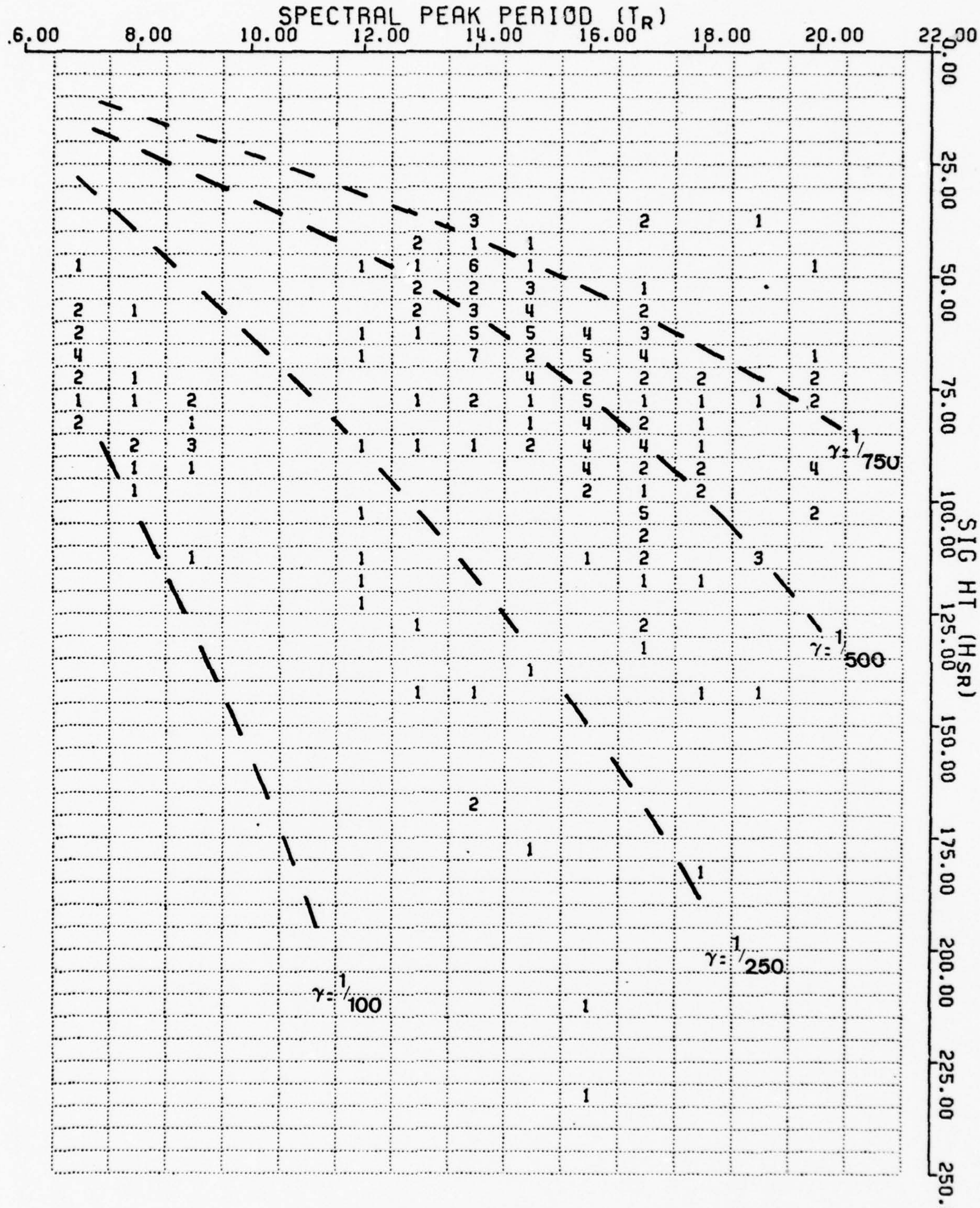

Figure 10. Height-Period Distribution of Selected Wave Records.

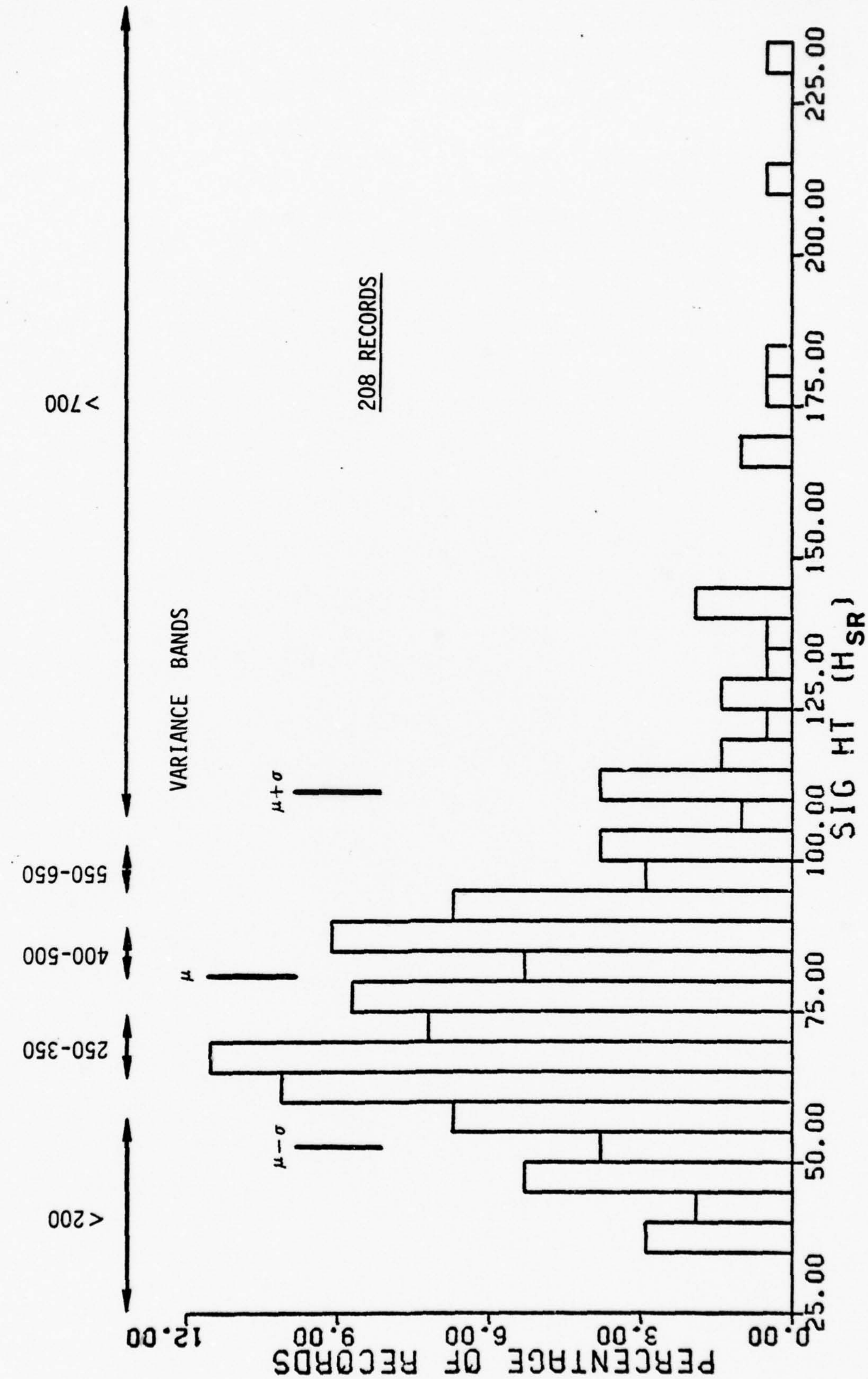

Figure 11. Distribution of H_{SR} in Wave Records Analyzed and Variance Bands Used.

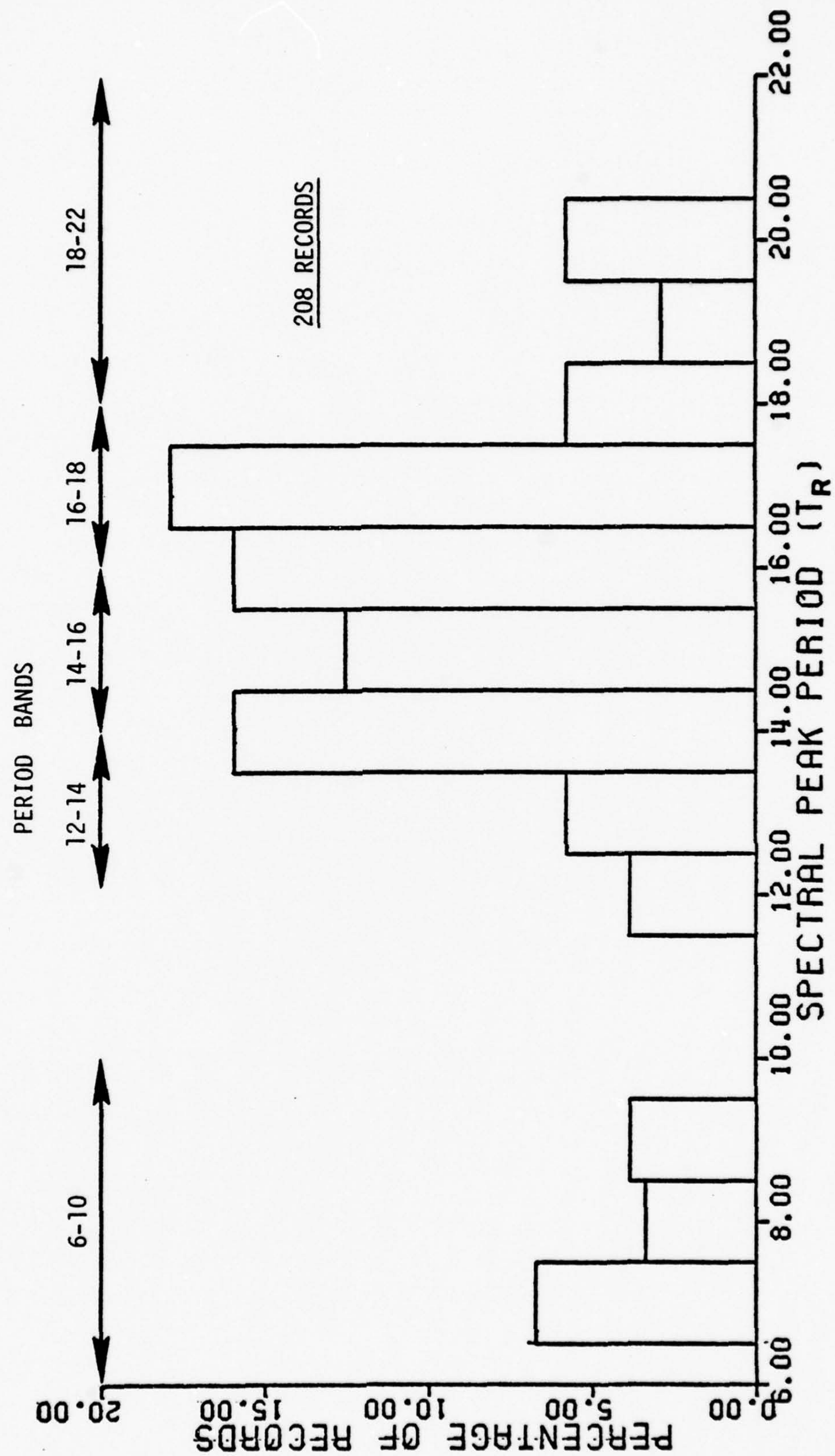

Figure 12. Distribution of Spectral Peak Period in Wave Records Analyzed.

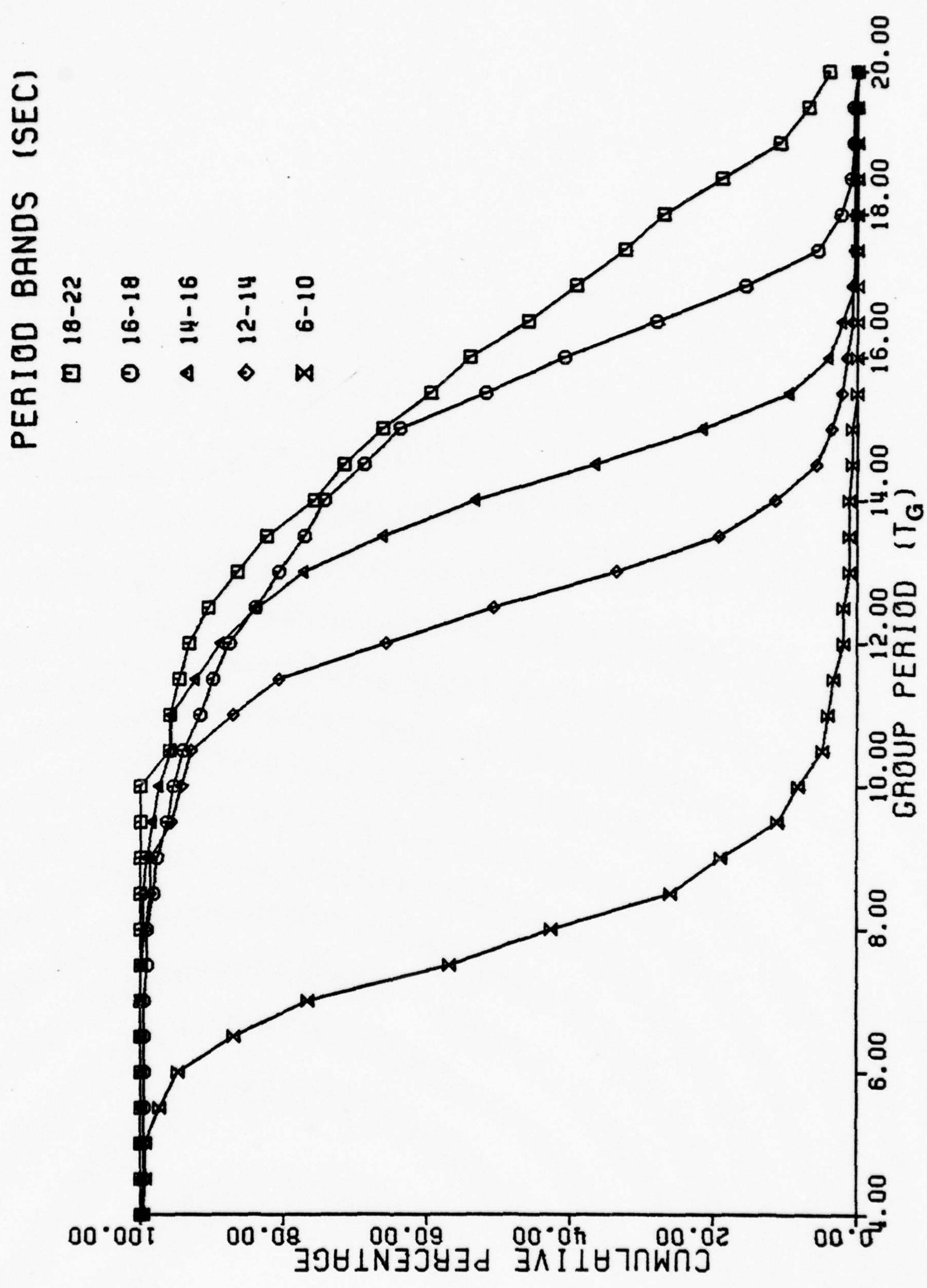

Figure 13. Distribution of T_G by Spectral Peak Period Bands.

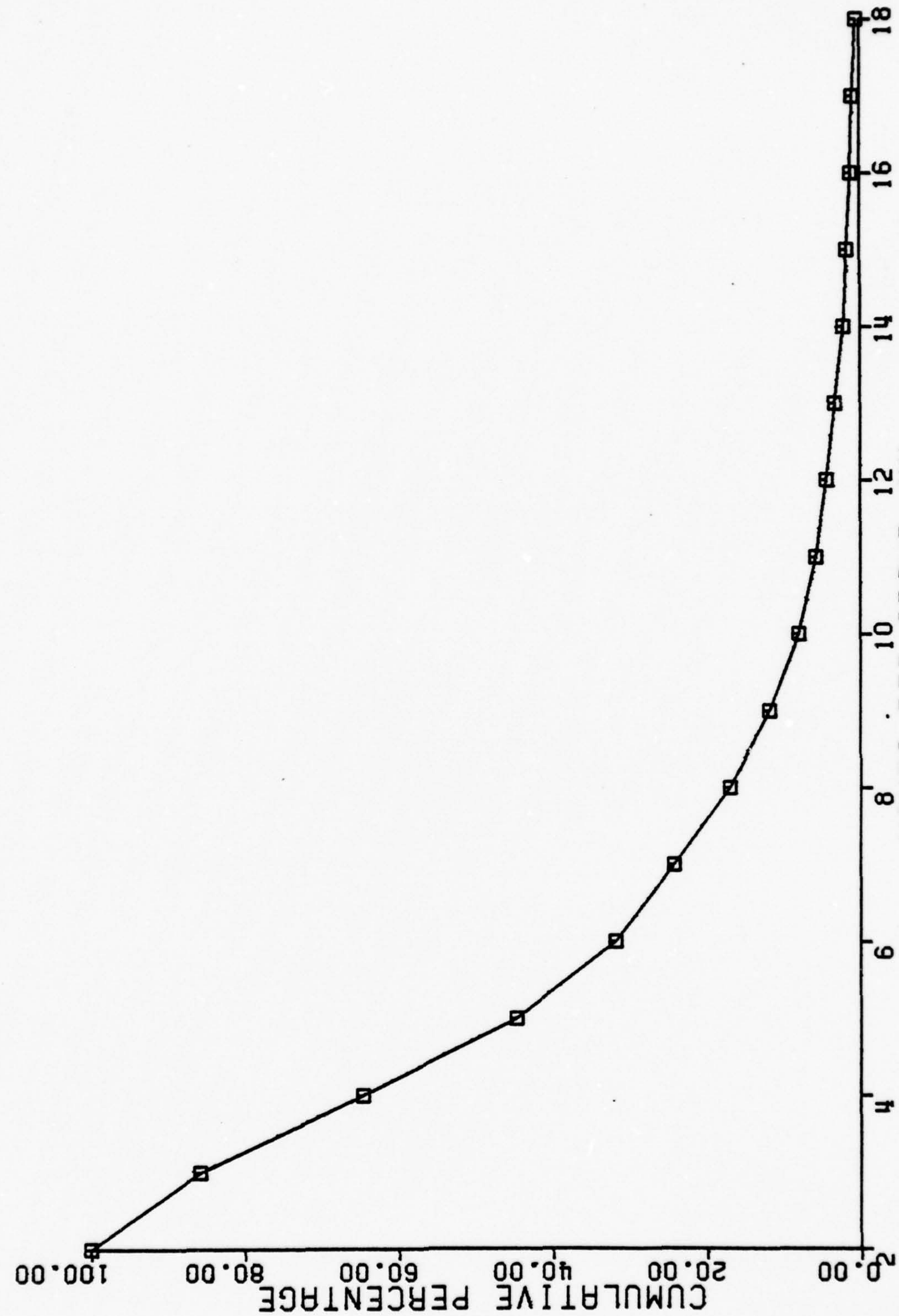

Figure 14. Distribution of N (1643 groups).

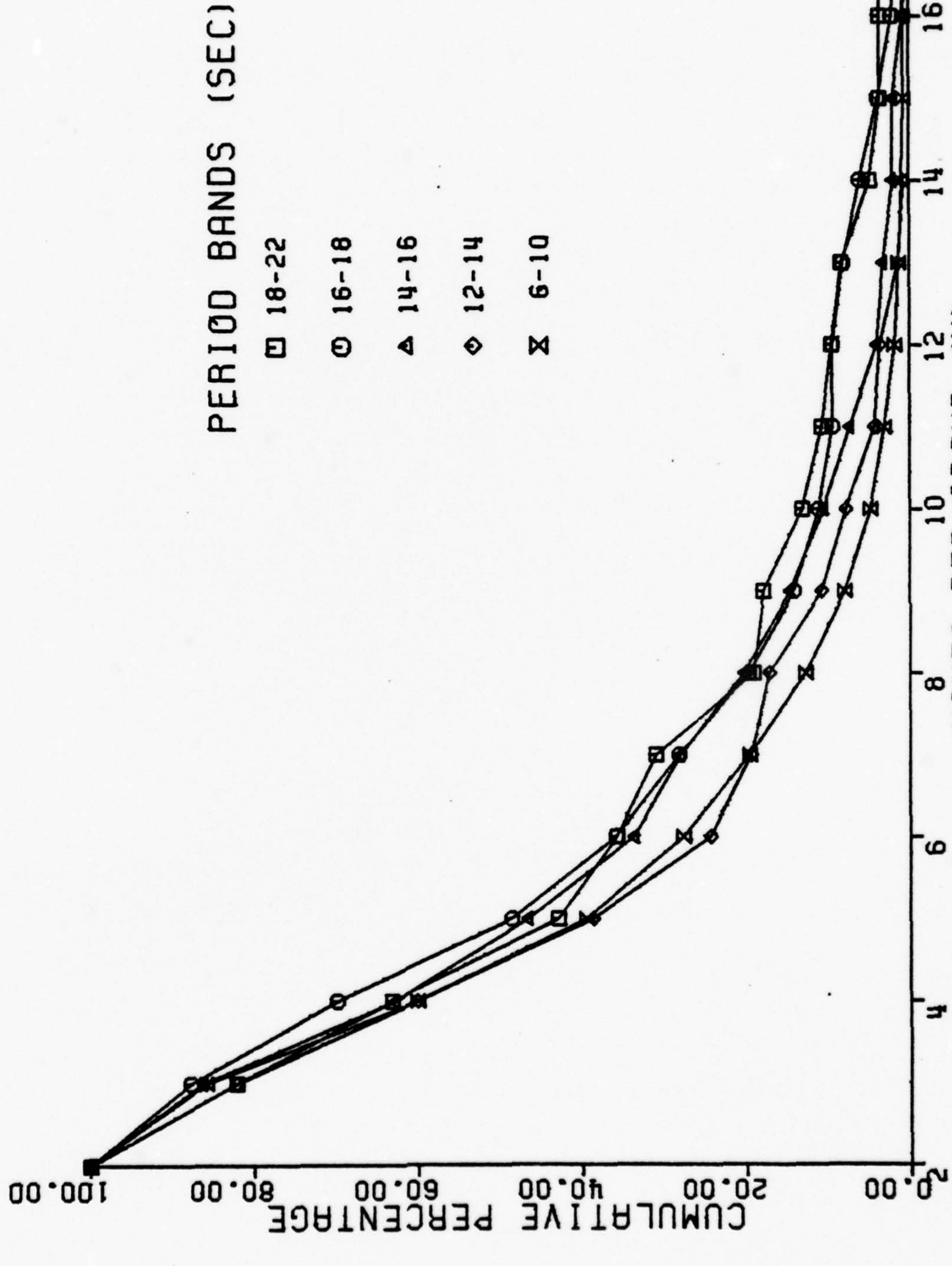

Figure 15. Distribution of N by Spectral Peak Period Bands.

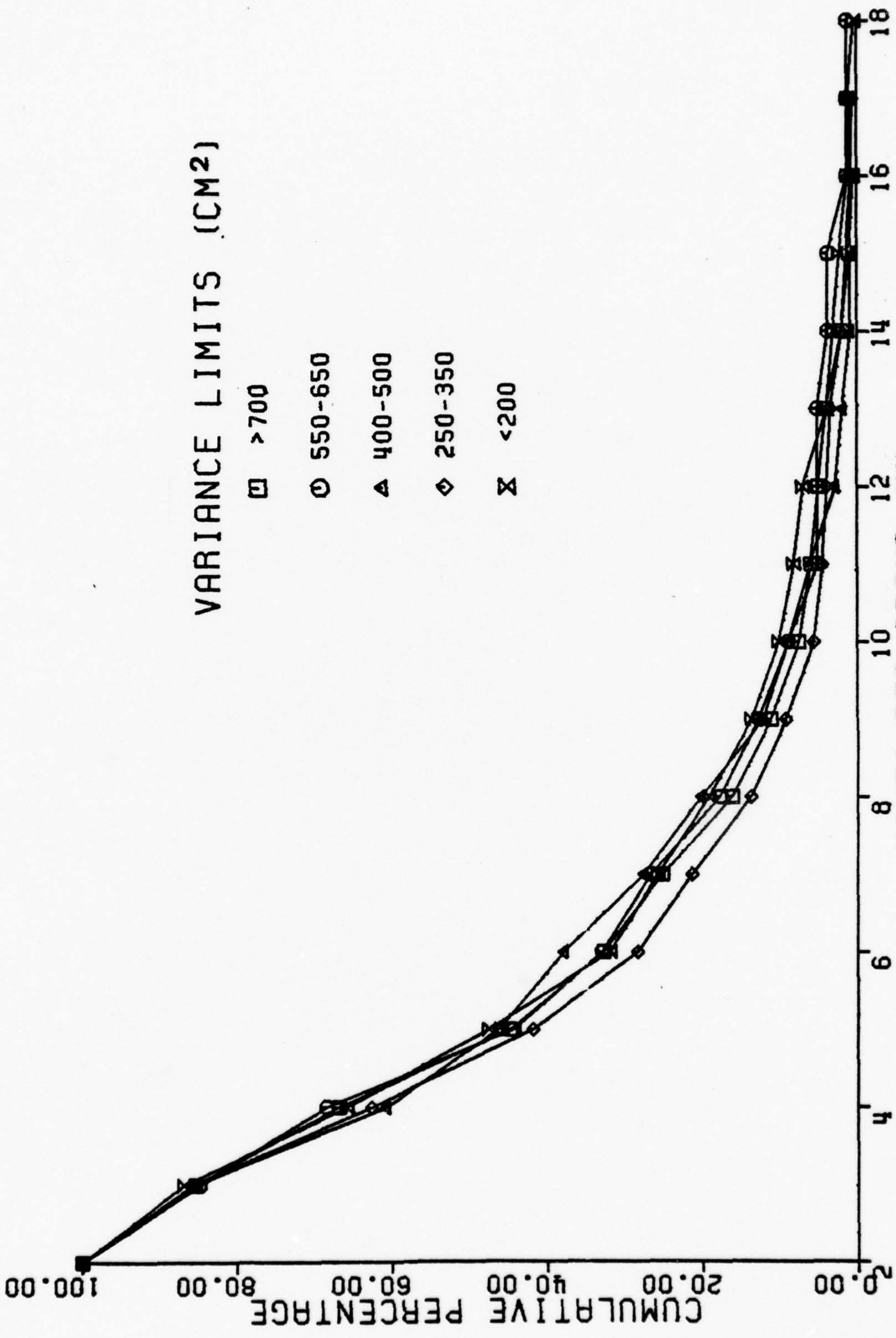

Figure 16. Distribution of N by Variance Bands.

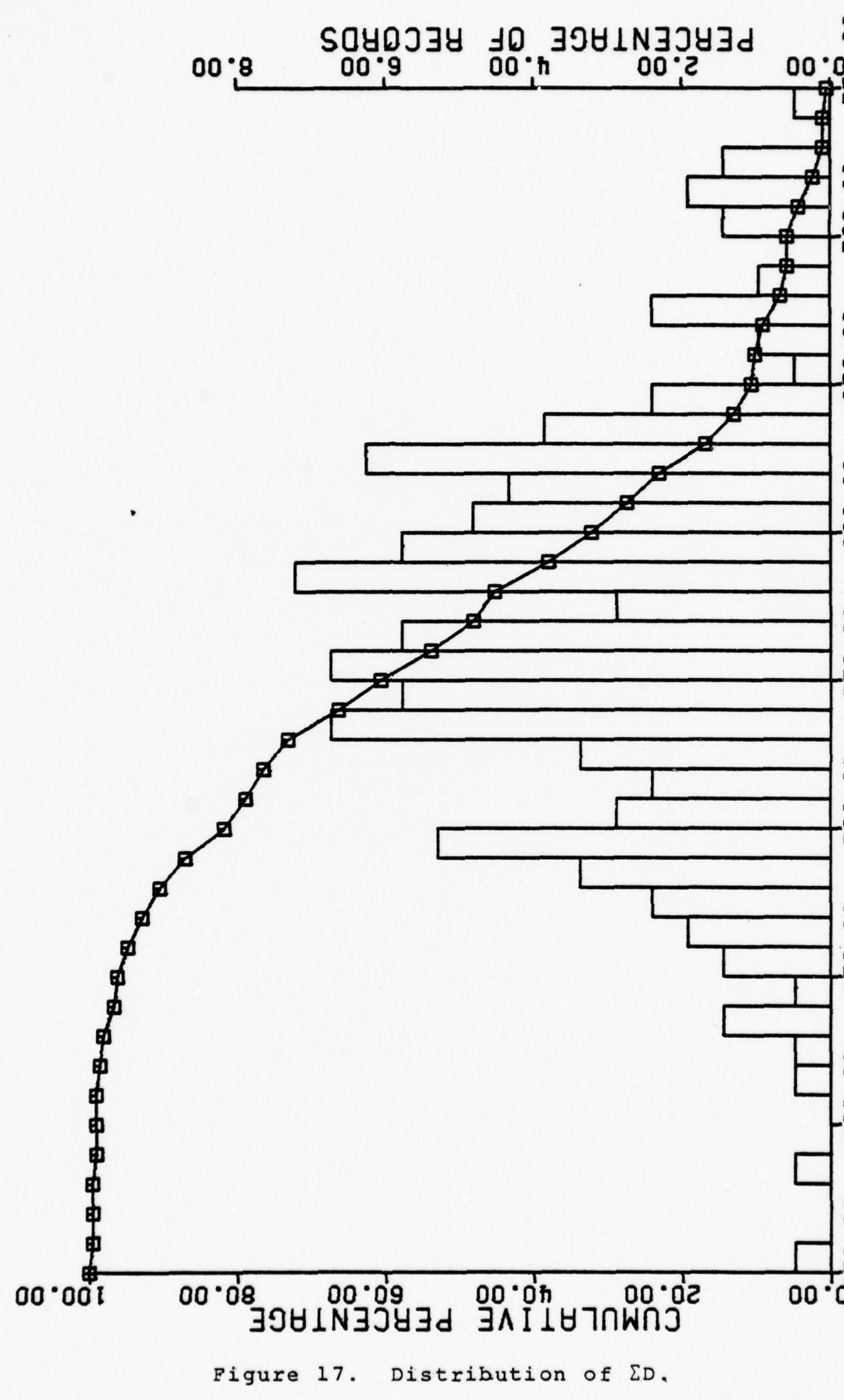

Figure 17. Distribution of ΣD.

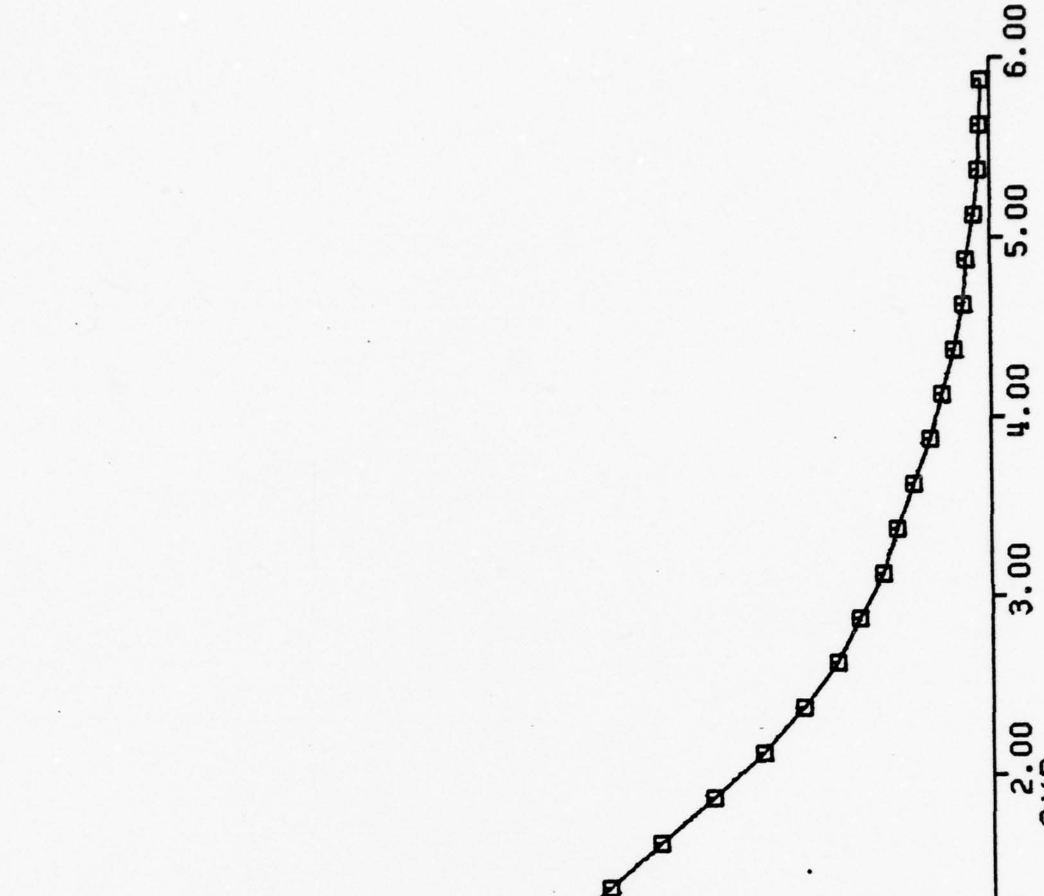

Figure 18. Distribution of $AVR_{\%}$ (1643 groups).

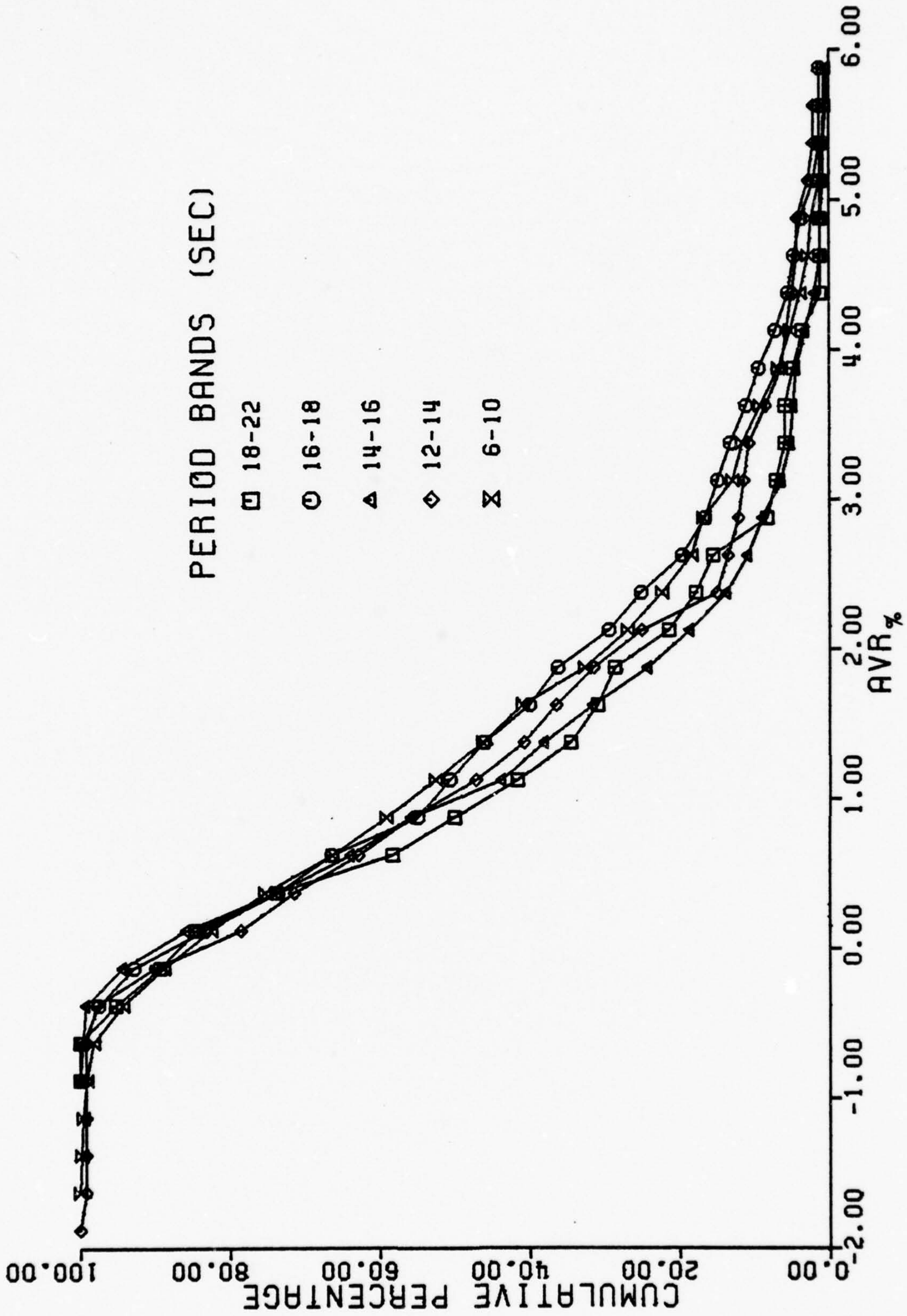

Figure 19. Distribution of $AVR_{\%}$ by Spectral Peak Period Bands.

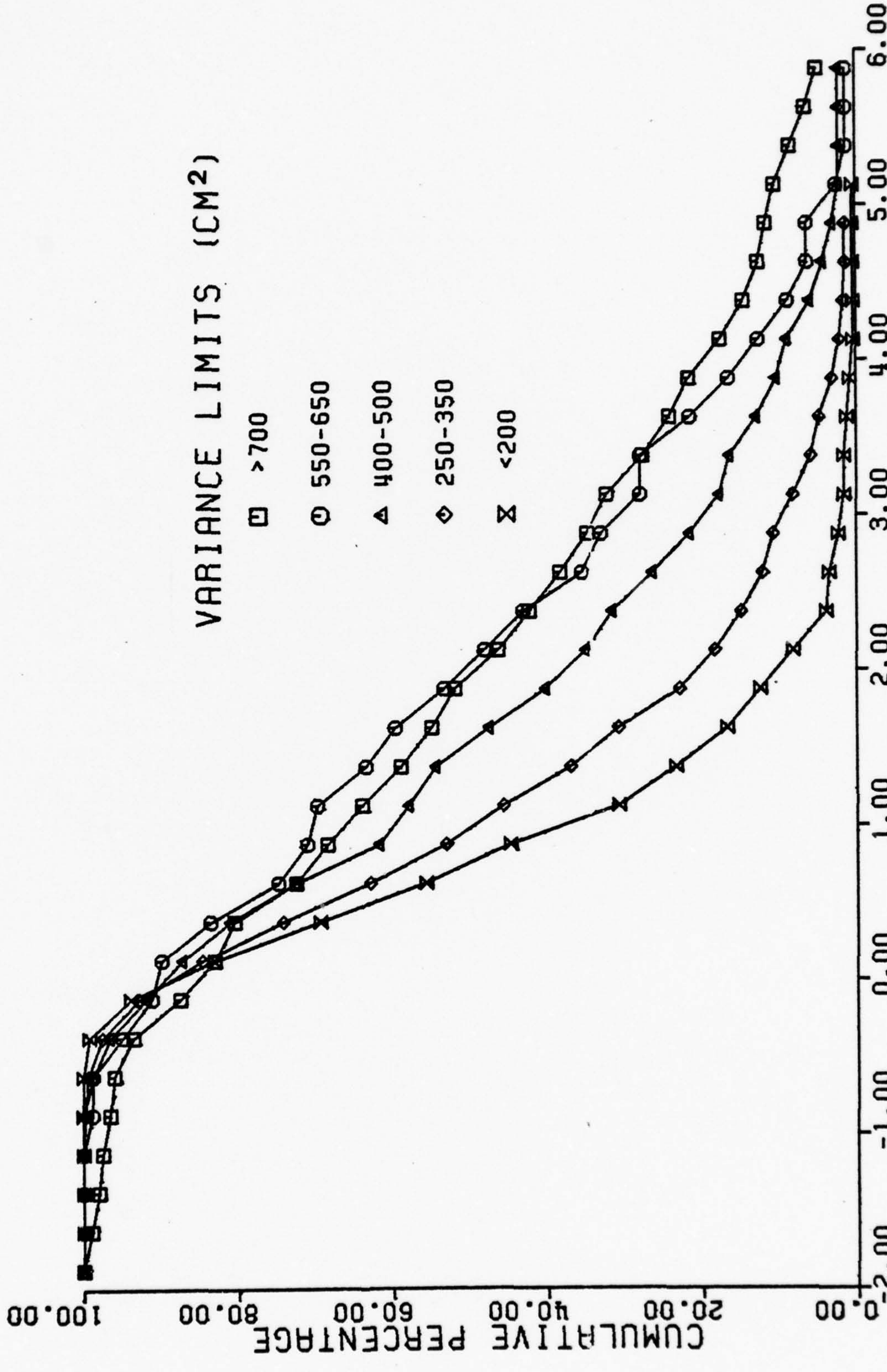

Figure 20. Distribution of $AVR_{\%}$ by Variance Bands.

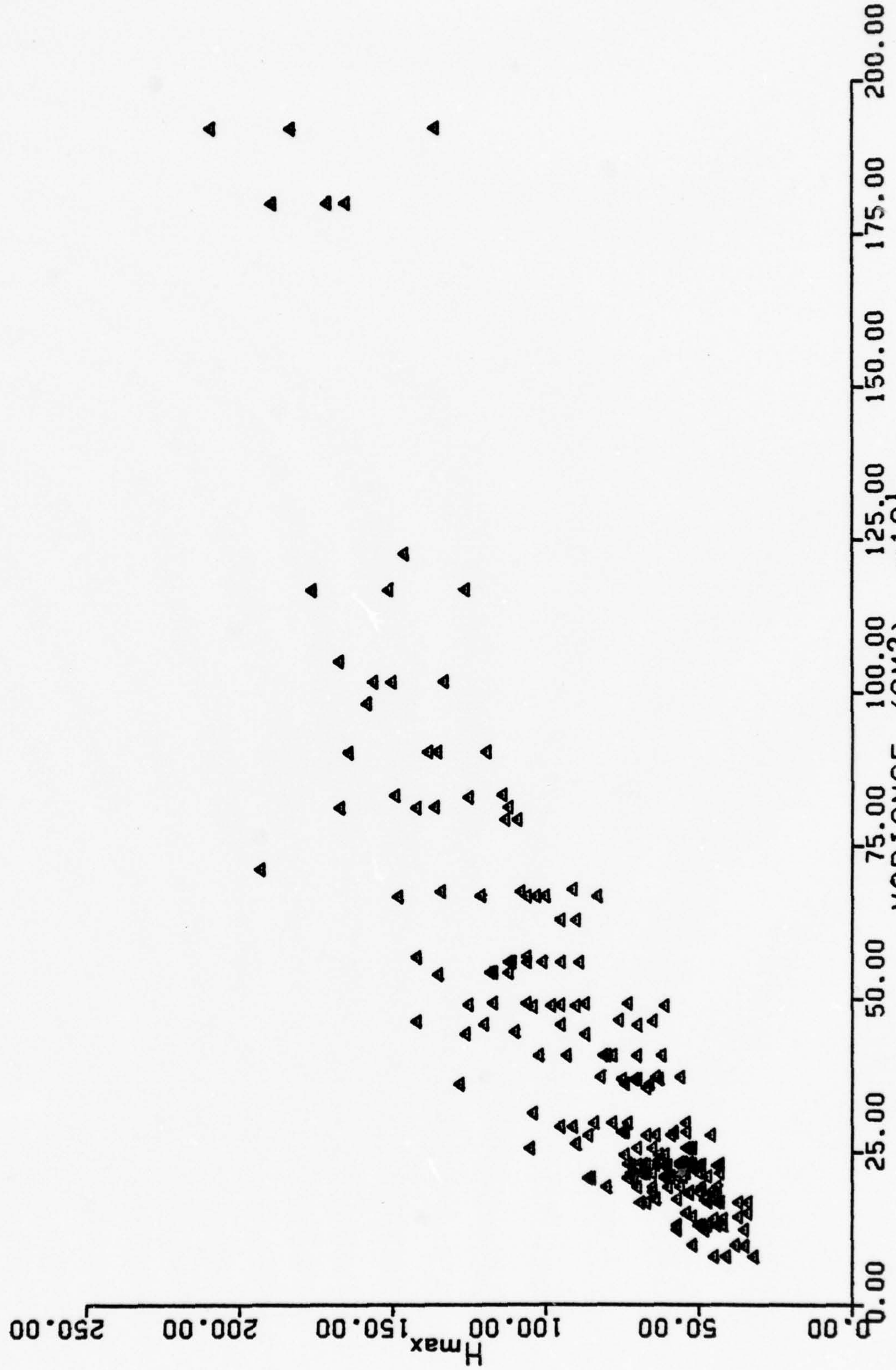

Figure 21. Variance vs H_{max}.

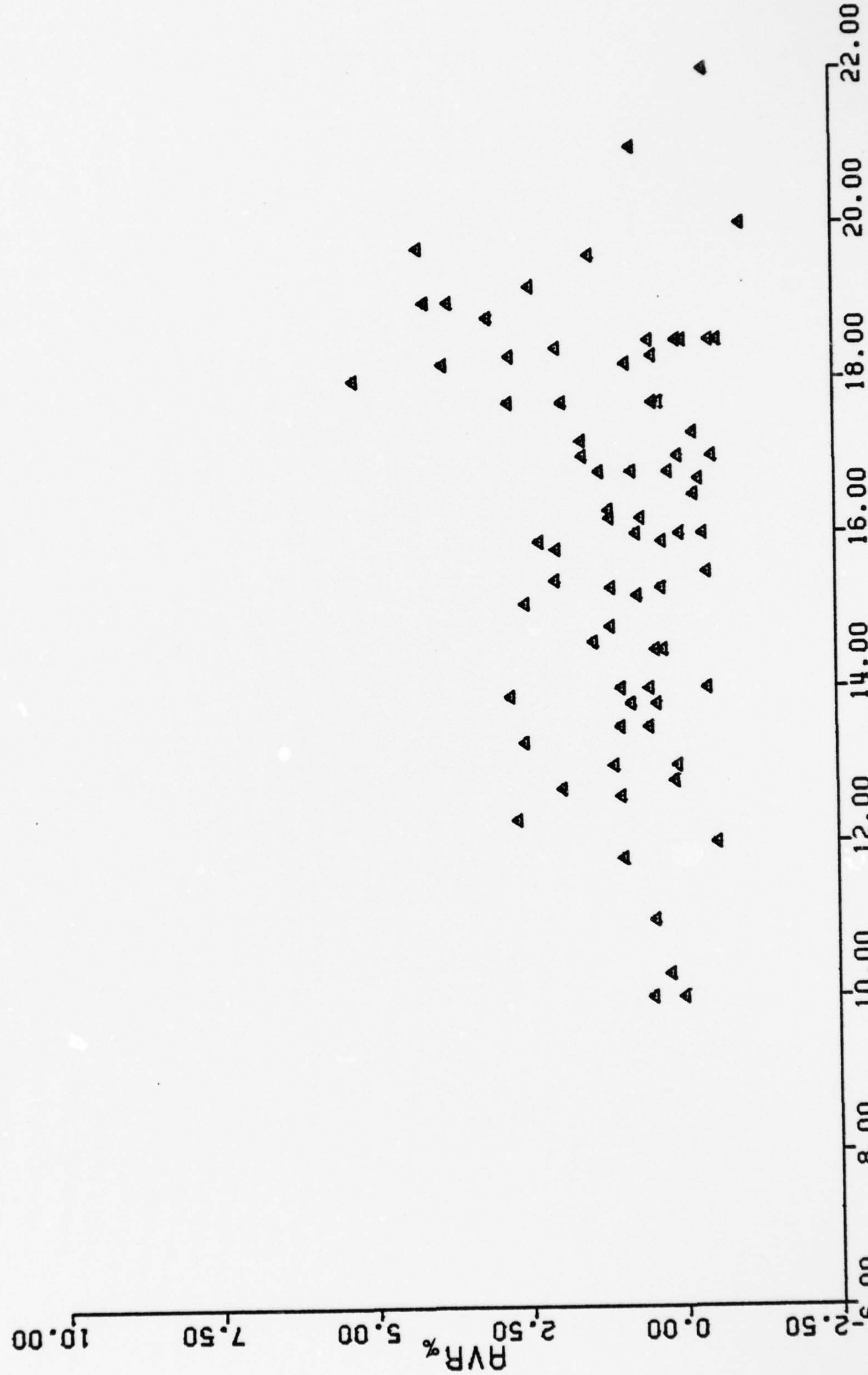

Figure 22. $AVR_{\%}$ vs T_G (18-22 sec band).

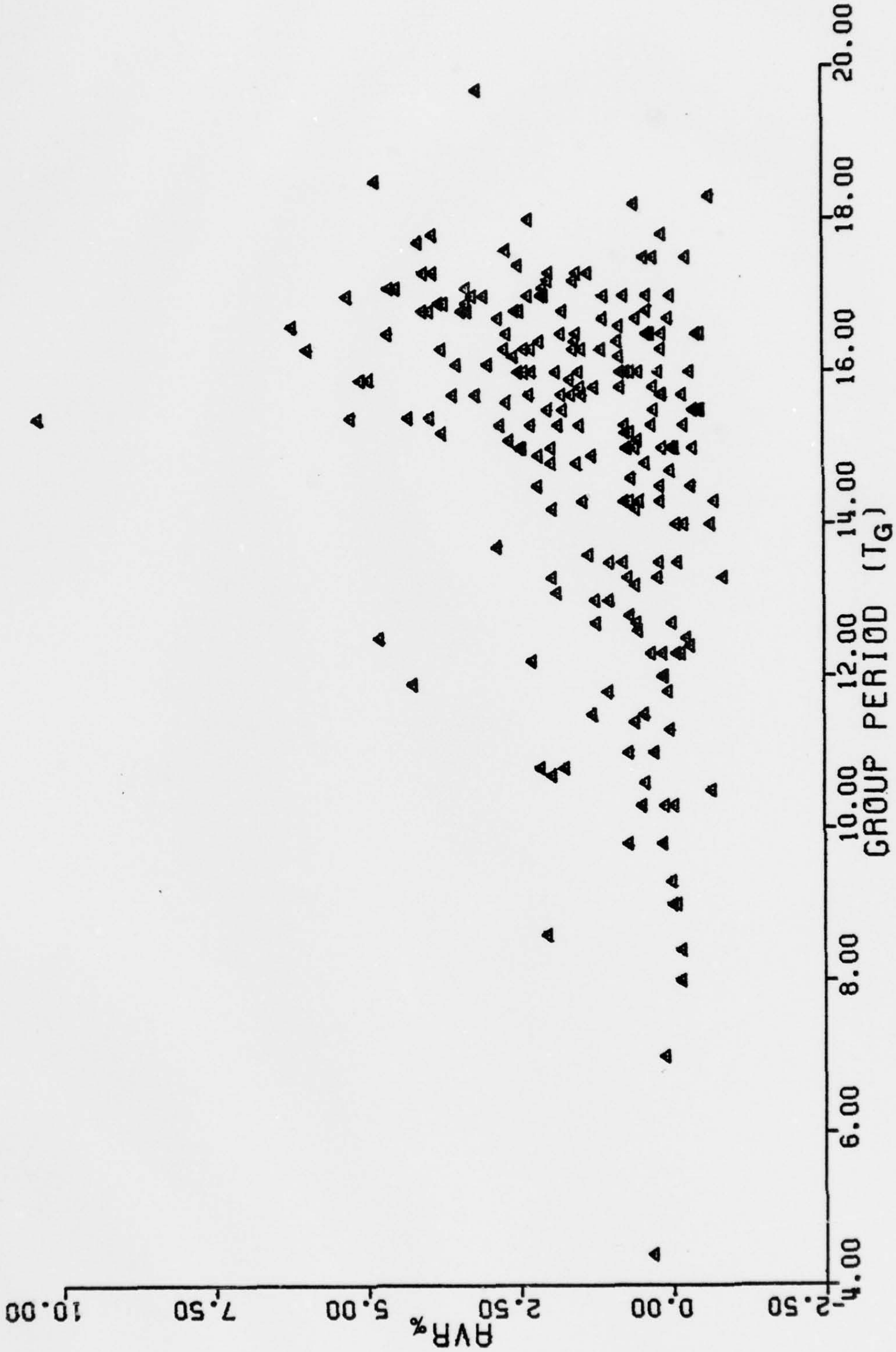

Figure 23. $AVR_{\%}$ vs T_G (16-18 sec band).

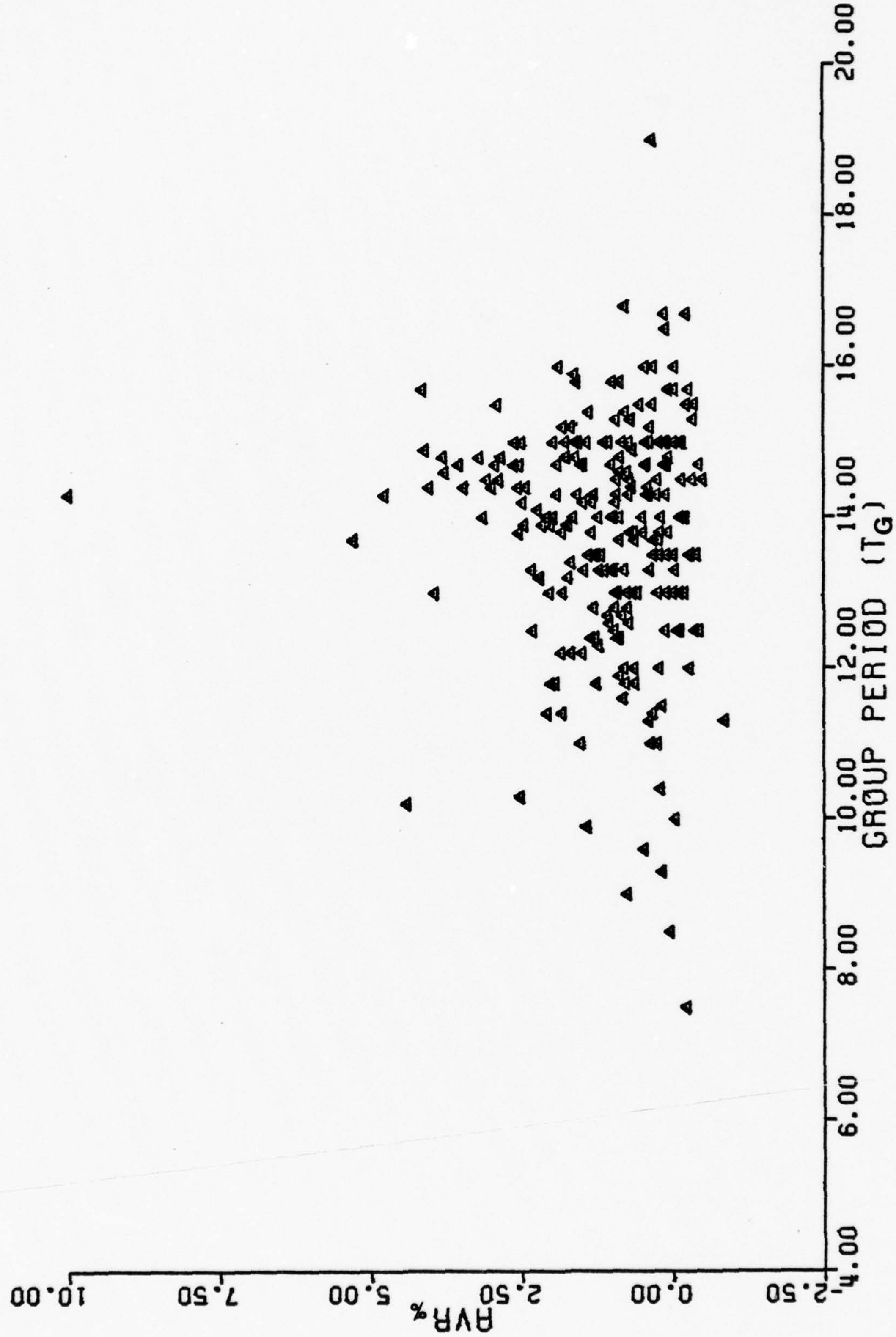

Figure 24. $AVR_{\%}$ vs T_G (14-16 sec band).

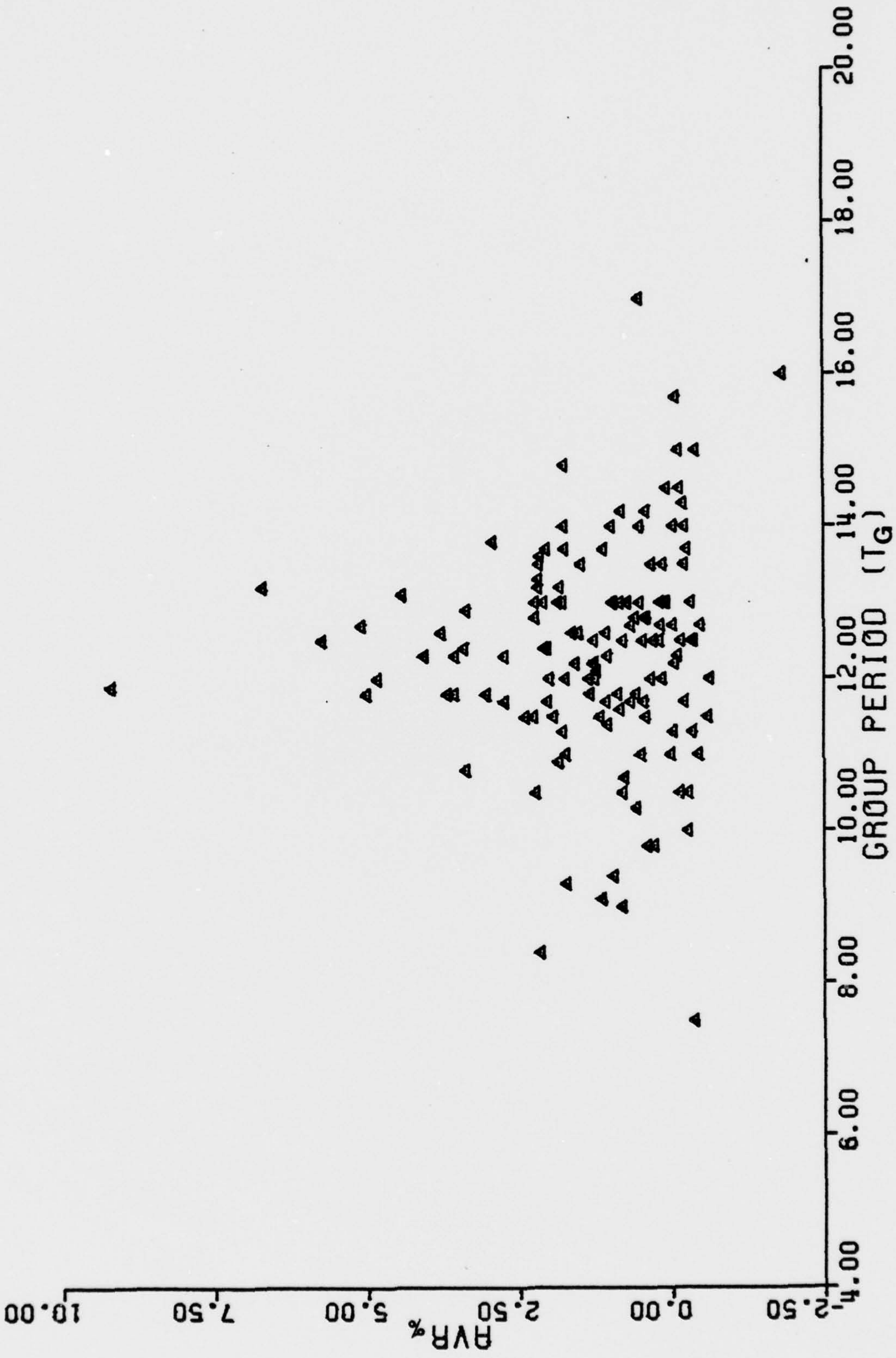

Figure 25. $AVR_{\%}$ vs T_G (12-14 sec band).

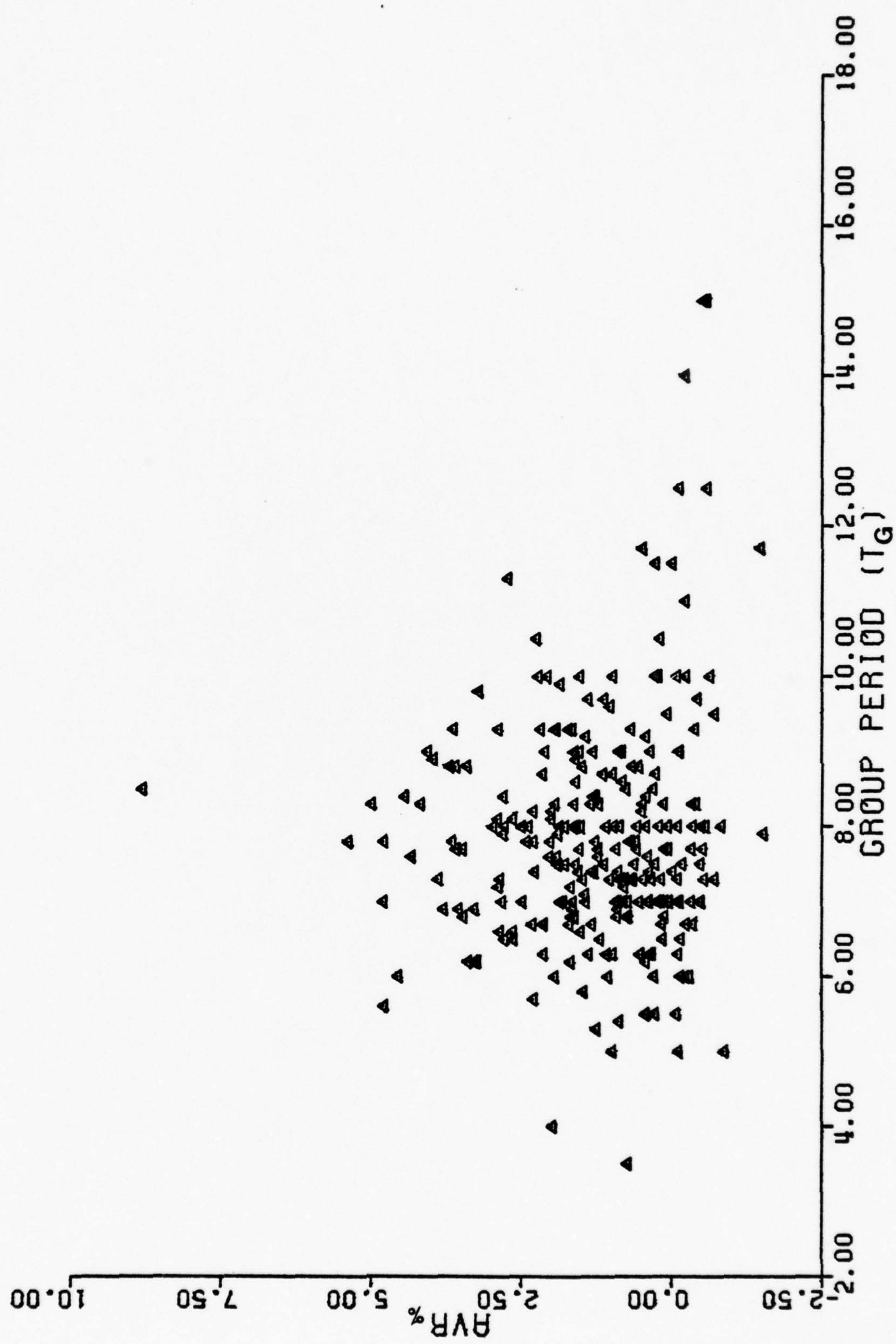

Figure 26. $AVR_{\%}$ vs T_G (6-10 sec band).

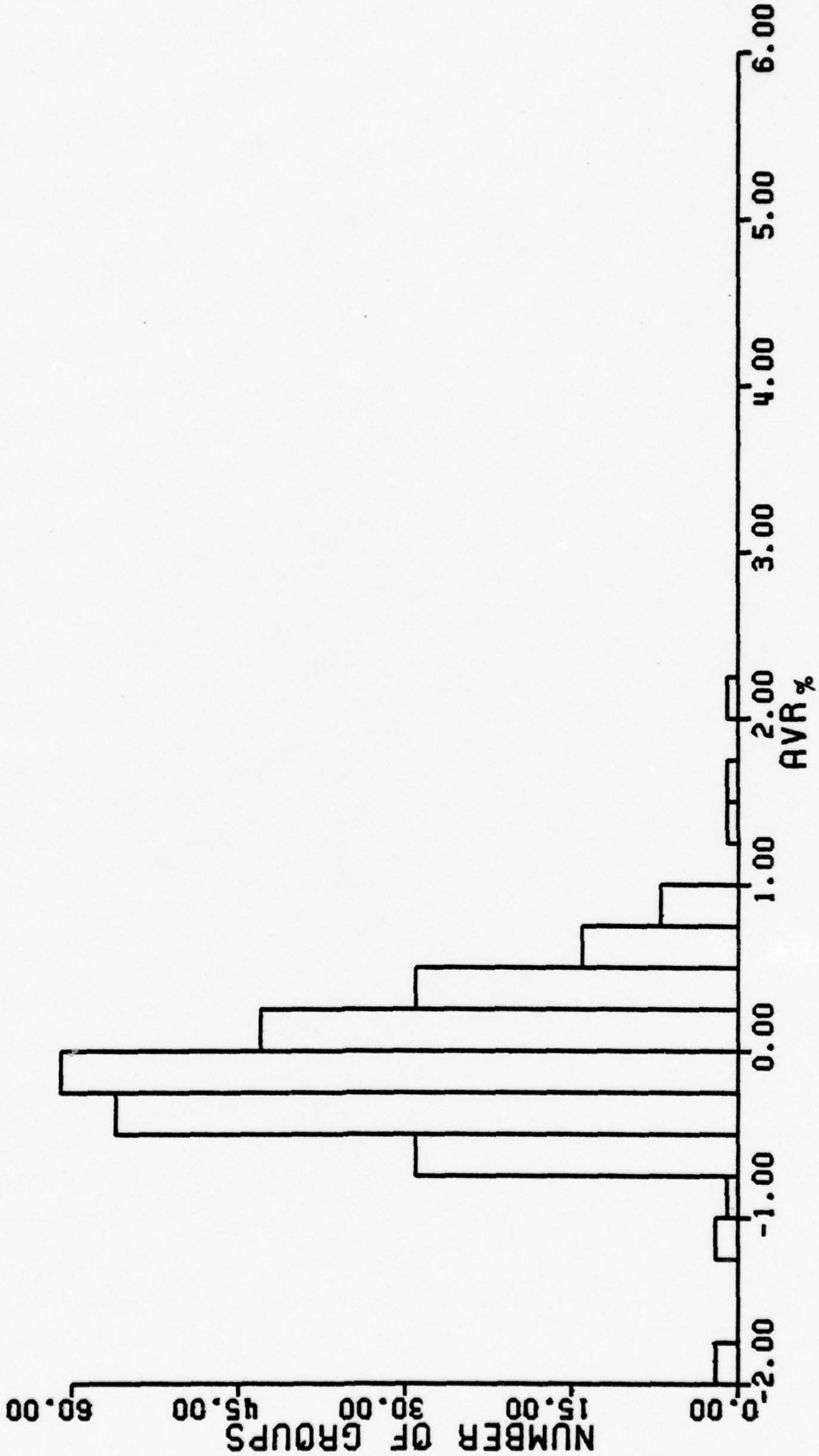

Figure 27. Distribution of $AVR_{\%}$ for N = 2.

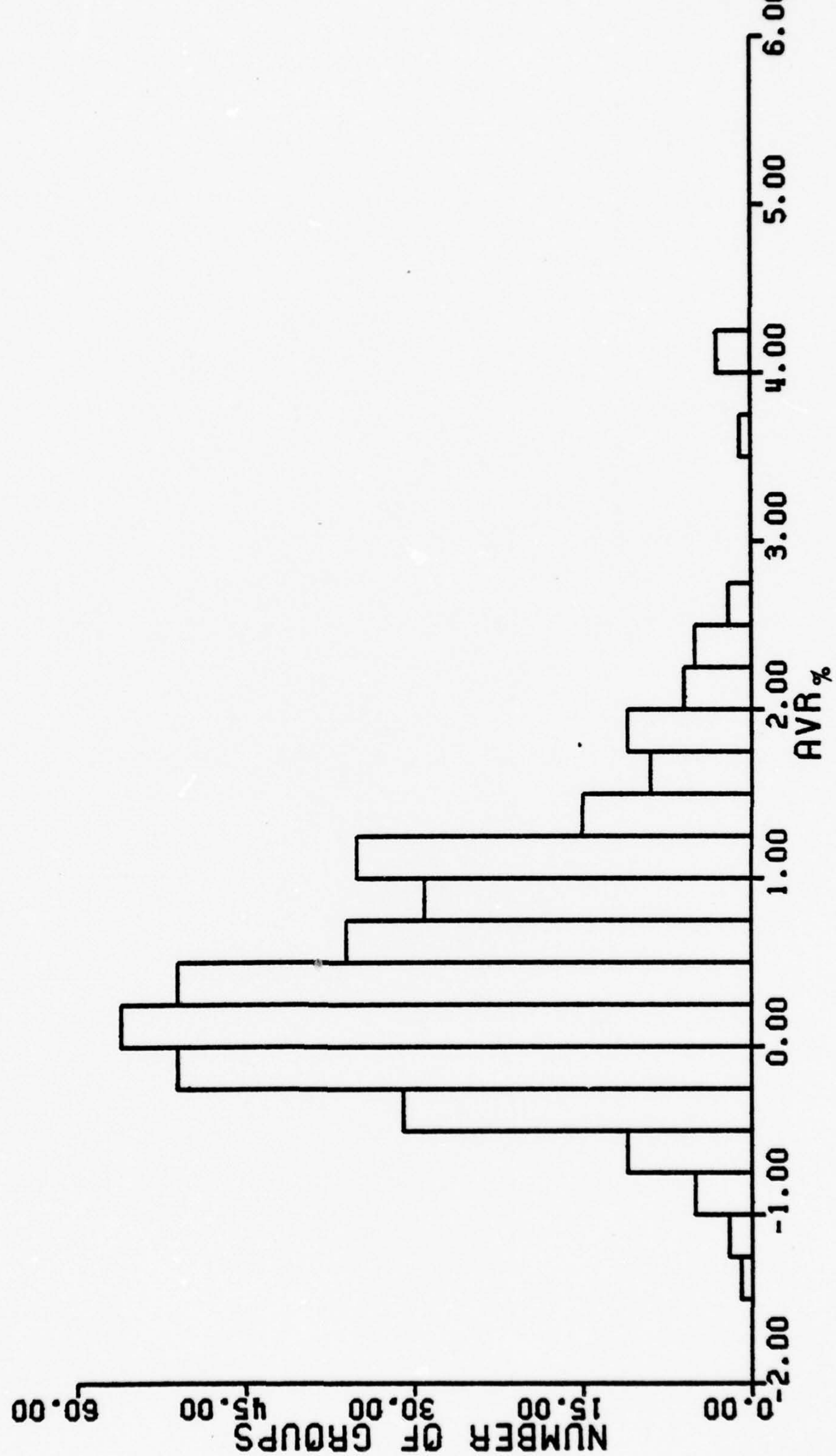

Figure 28. Distribution of $AVR_{\%}$ for N = 3.

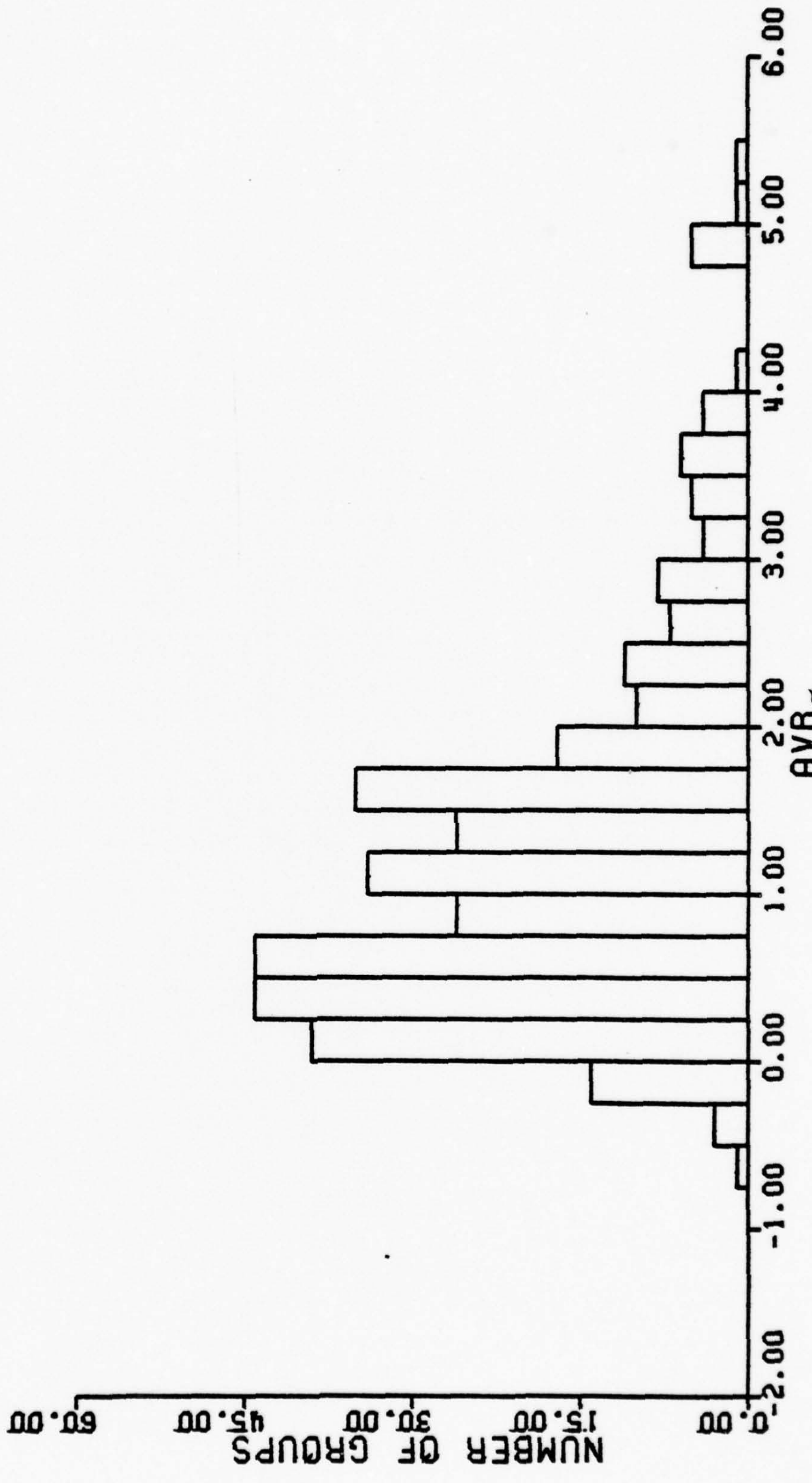

Figure 29. Distribution of $AVR_{\%}$ for N = 4.

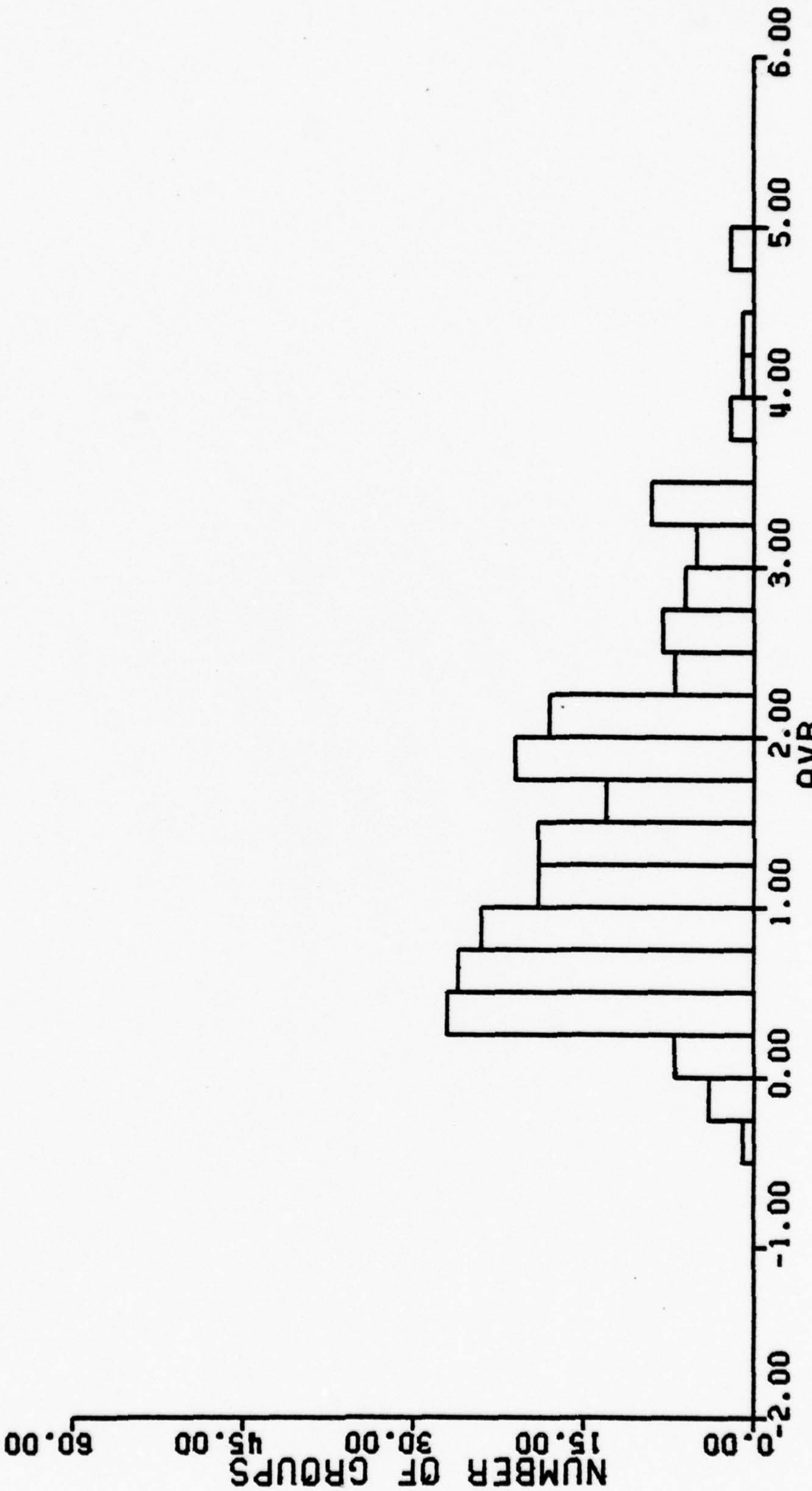

Figure 30. Distribution of $AVR_{\%}$ for N = 5.

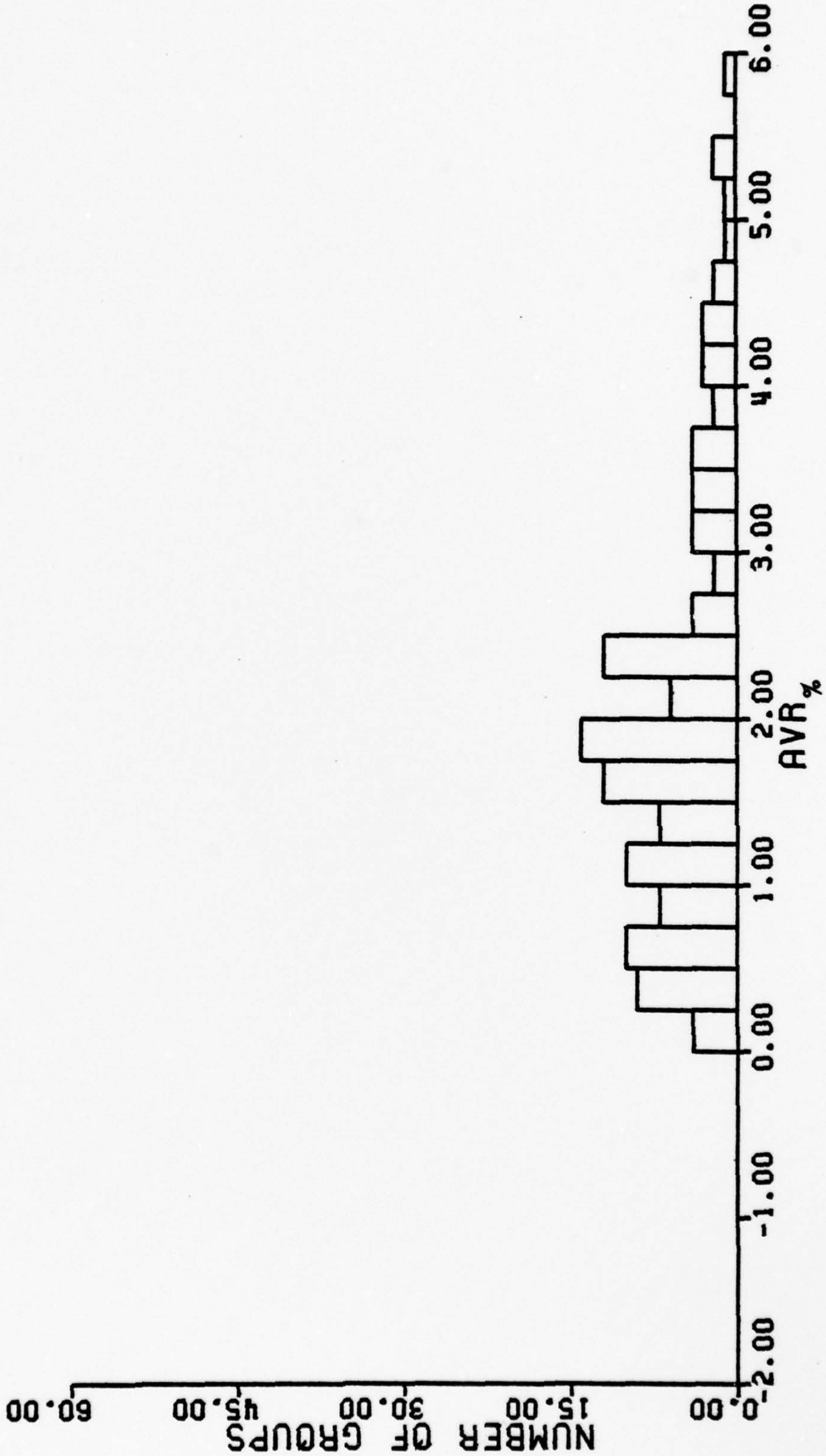

Figure 31. Distribution of $AVR_{\%}$ for N = 6.

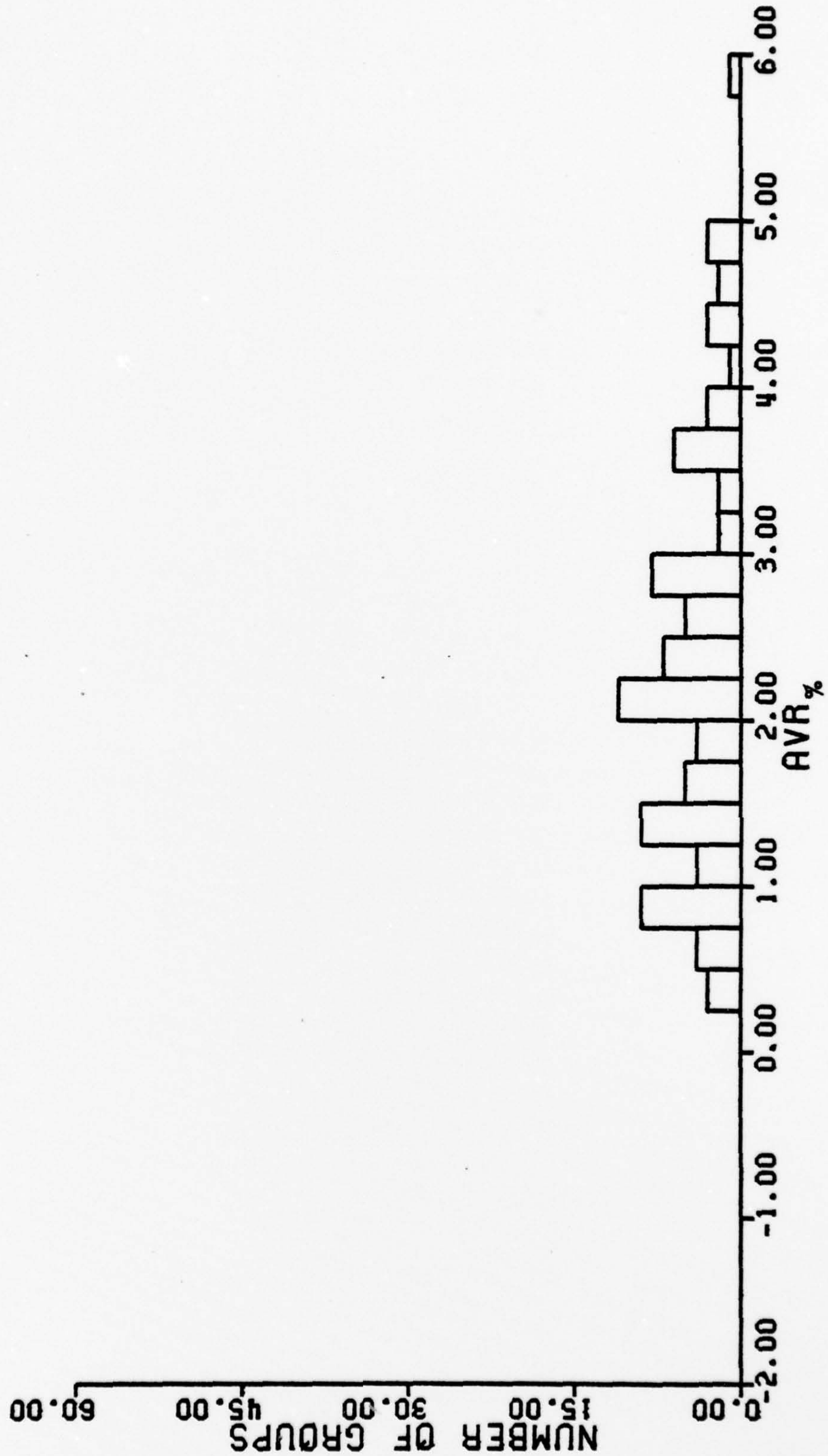

Figure 32. Distribution of $AVR_{\%}$ for N = 8.

Figure 33. Distribution of $AVR_{\%}$ for N = 10.

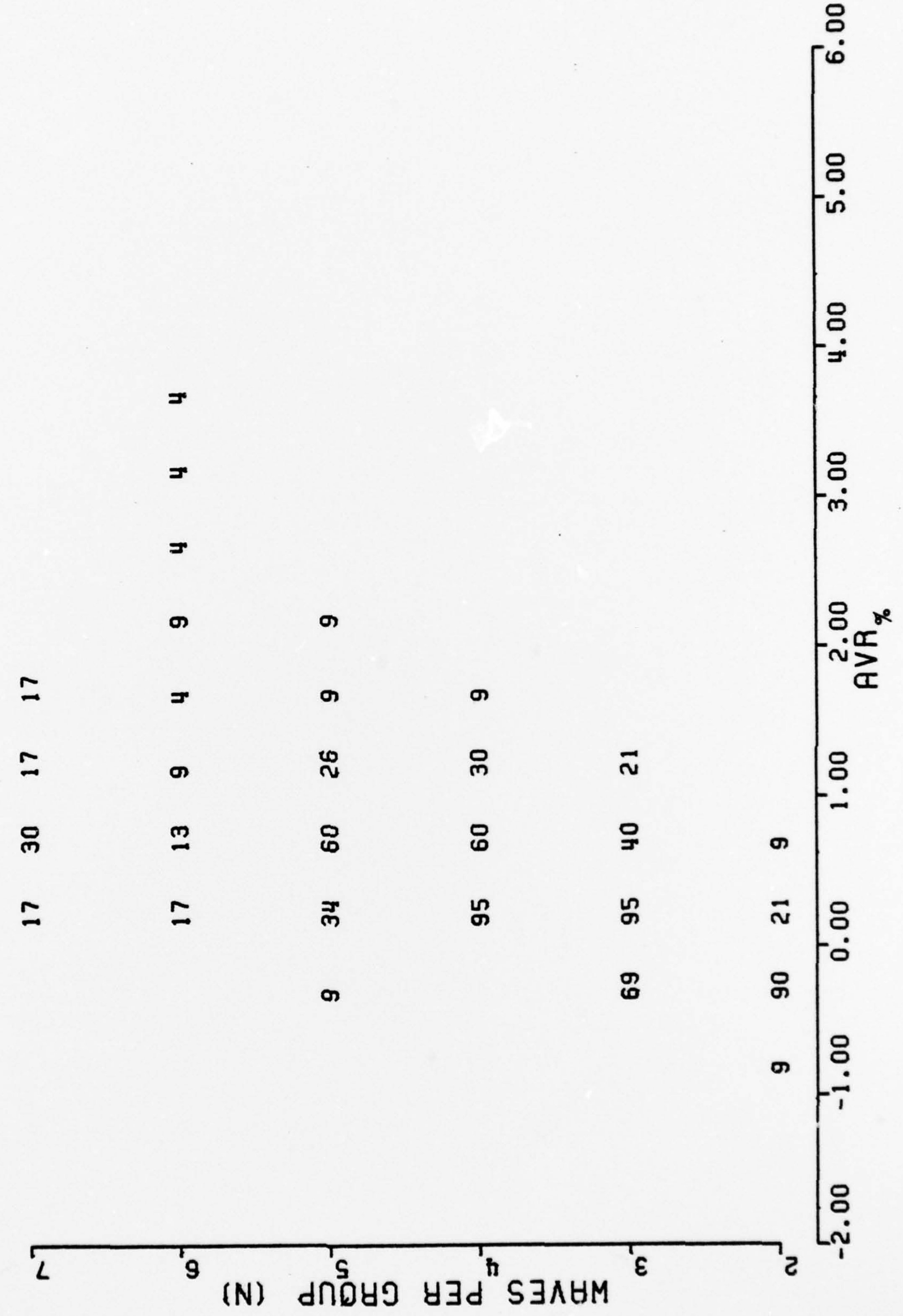

Figure 34. AVR$_{\%}$ vs N for $V_R < 200$ cm^2 (percentage x 10^{-1}).

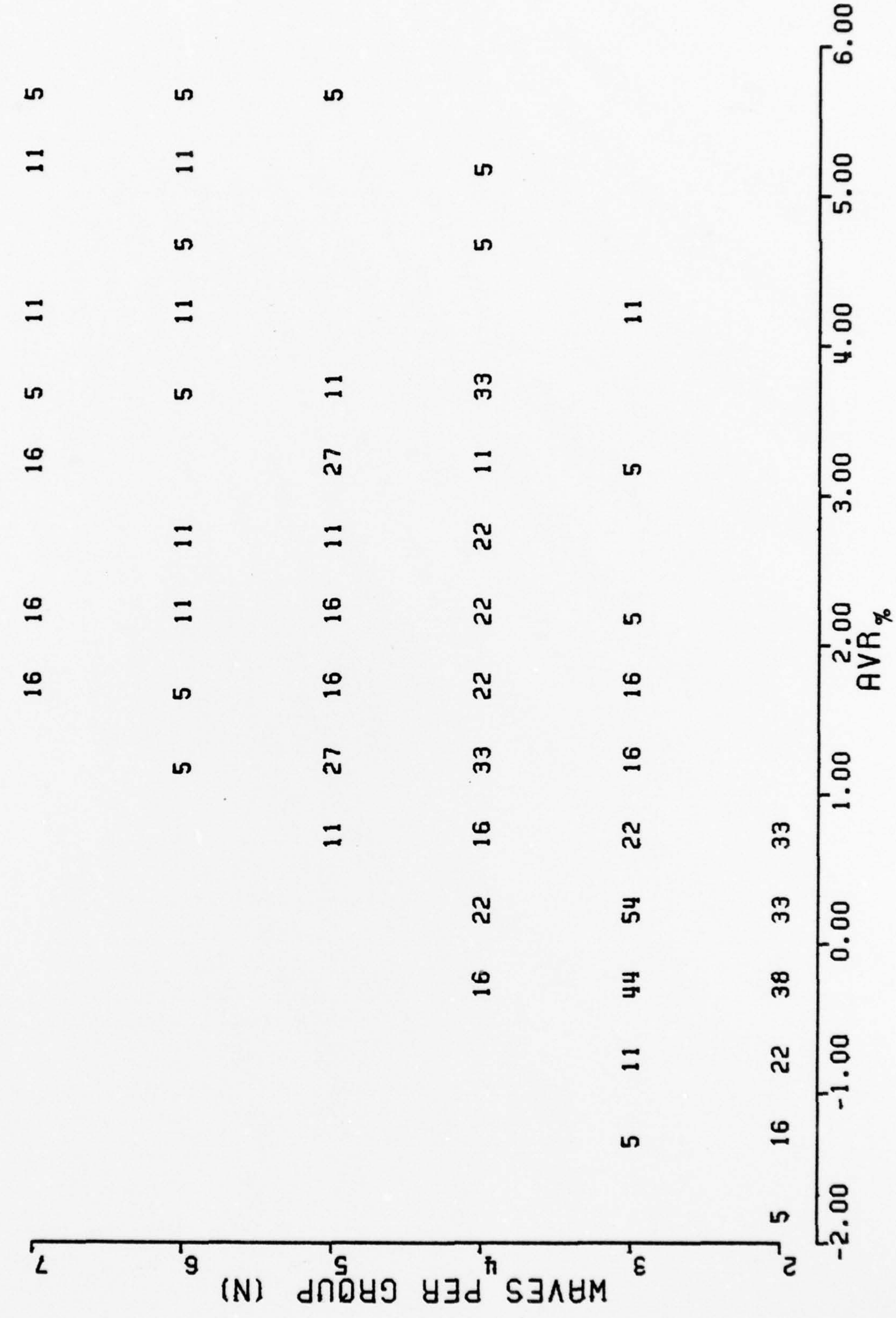

Figure 35. AVR$_{\%}$ vs N for $V_R > 700$ cm^2 (percentage x 10^{-1}).

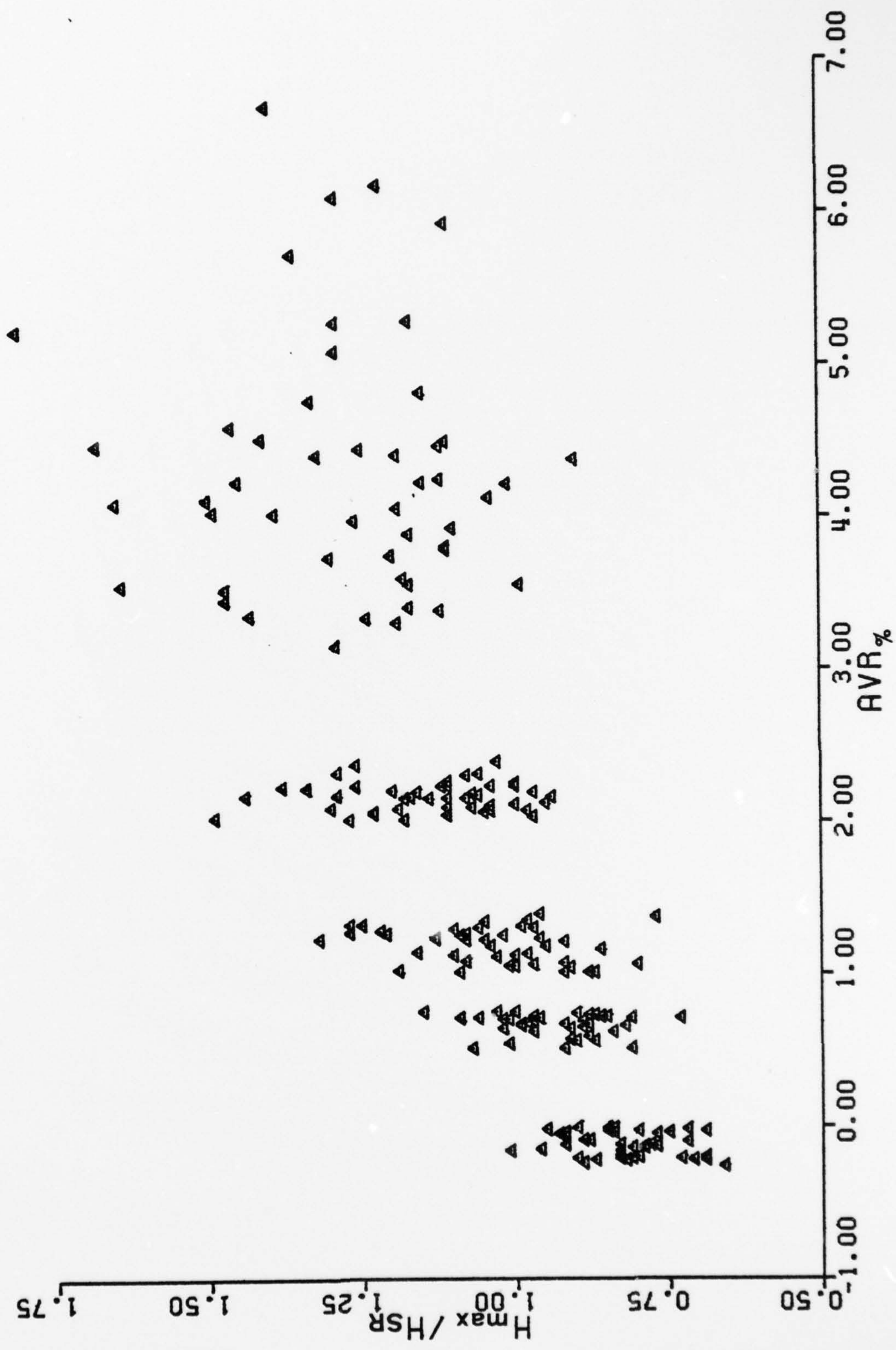

Figure 36. $AVR_{\%}$ vs H_{max}/H_{SR}.

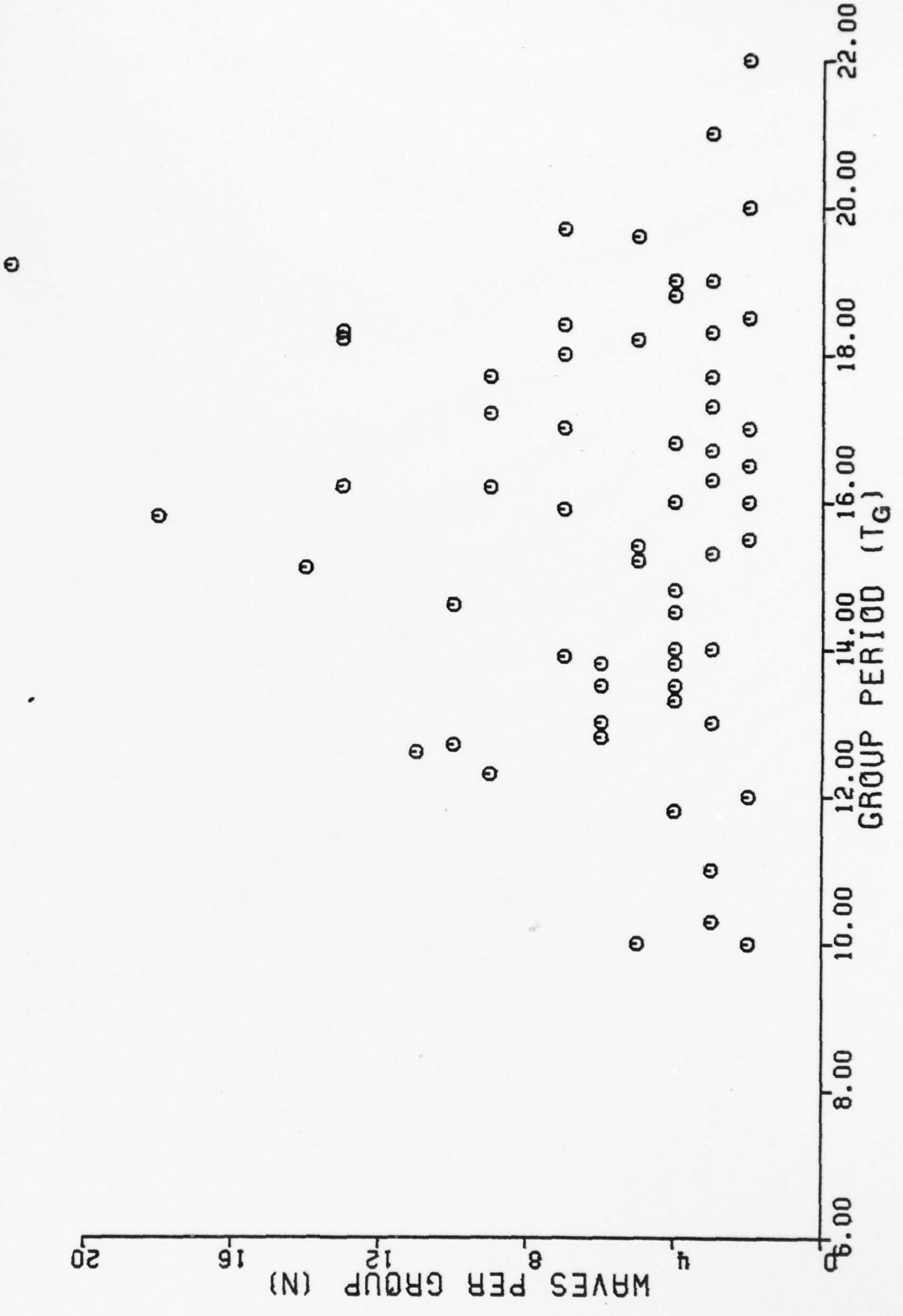

Figure 37. N vs T_G (18-22 sec band).

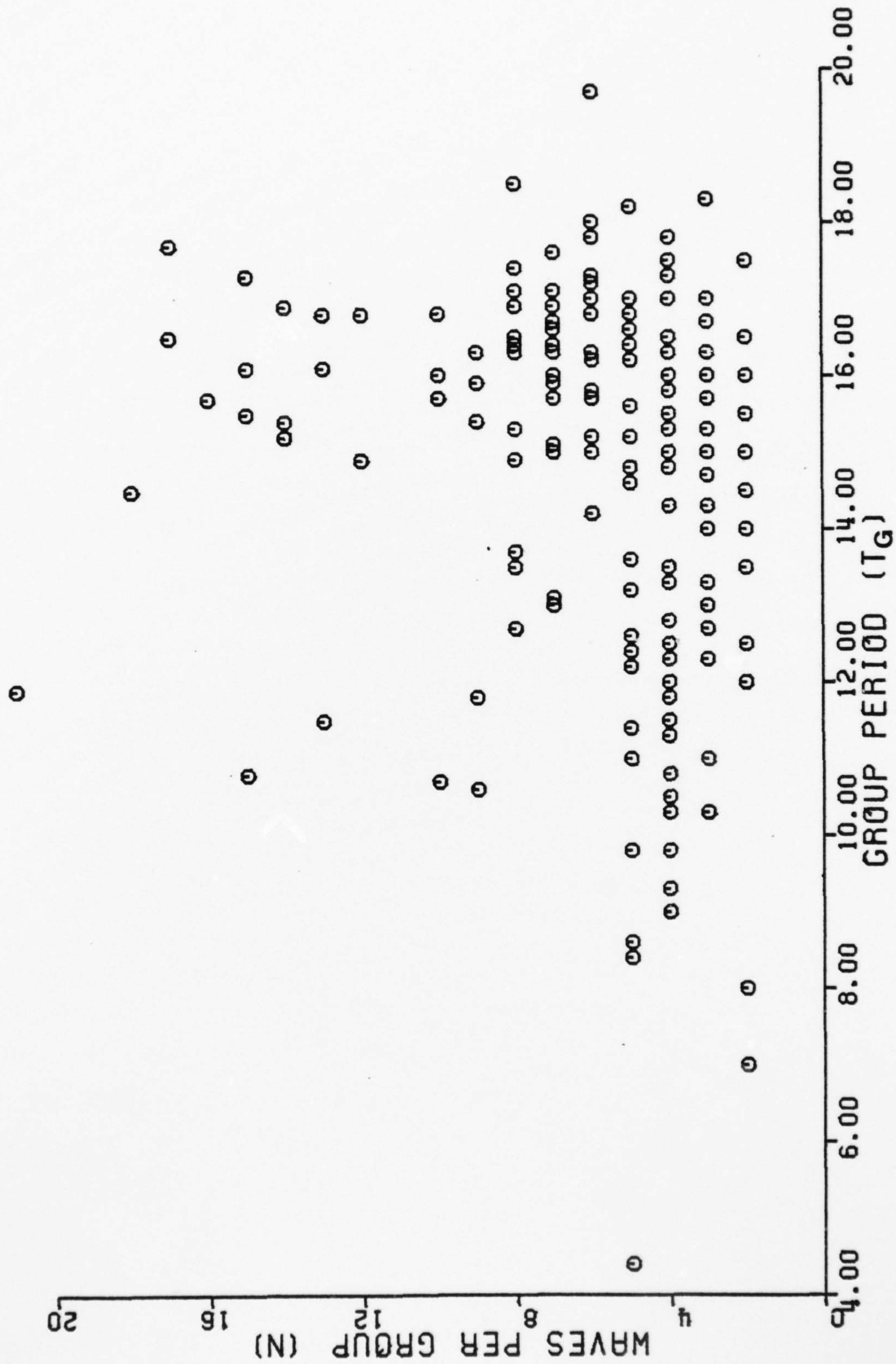

Figure 38. N vs T_G (16-18 sec band).

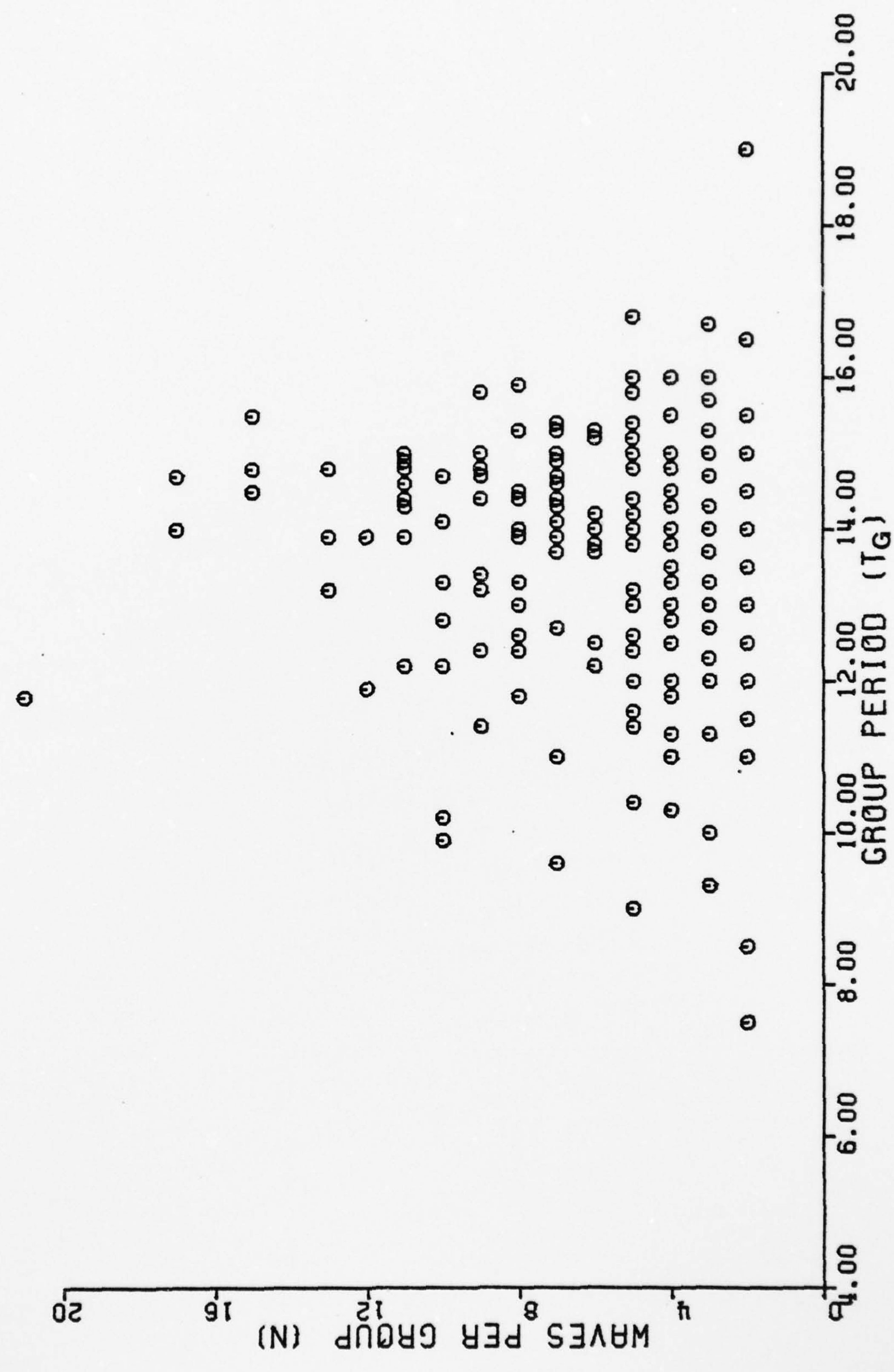

Figure 39. N vs T_G (14-16 sec band).

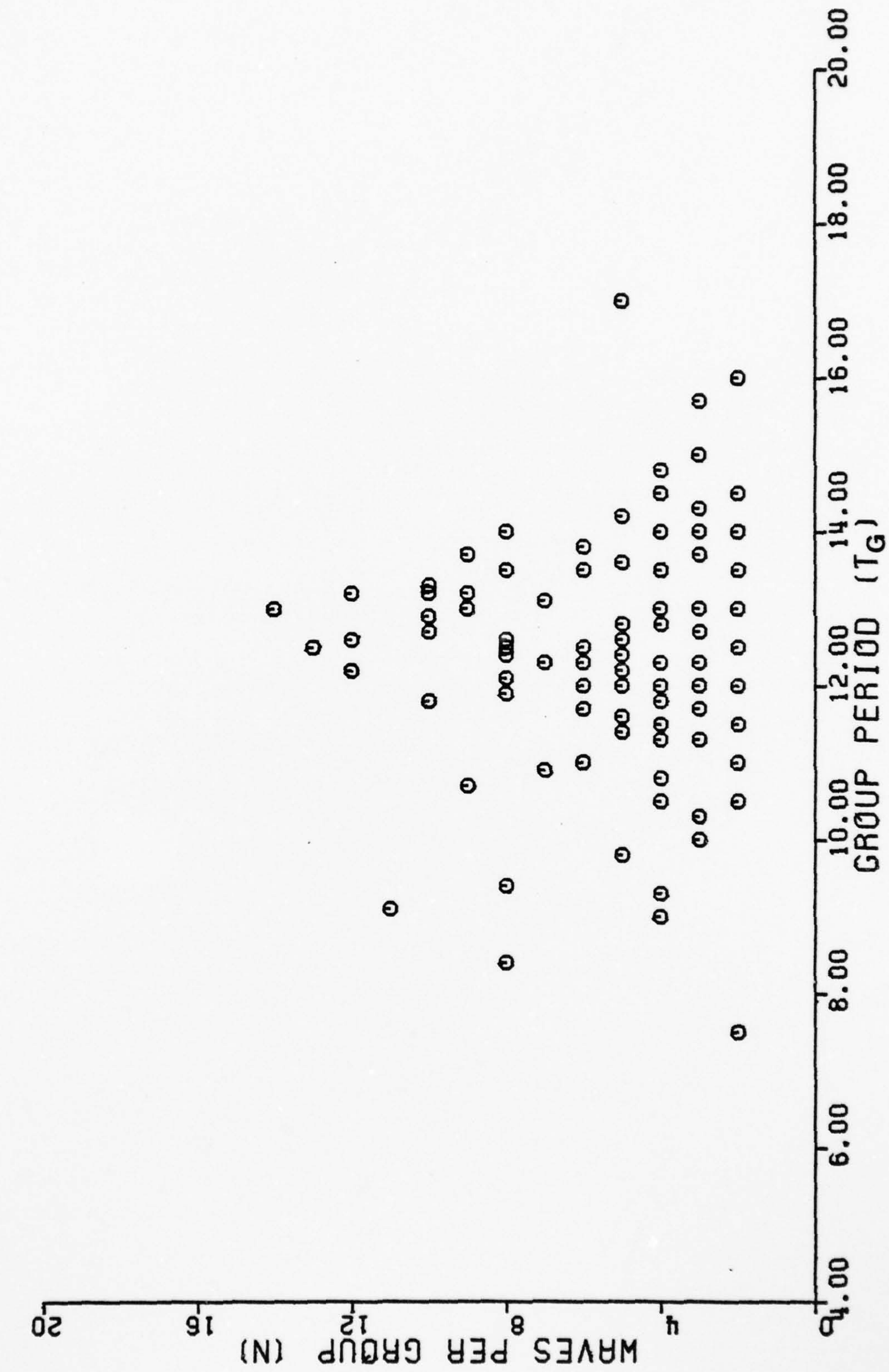

Figure 40. N vs T_G (12-14 sec band).

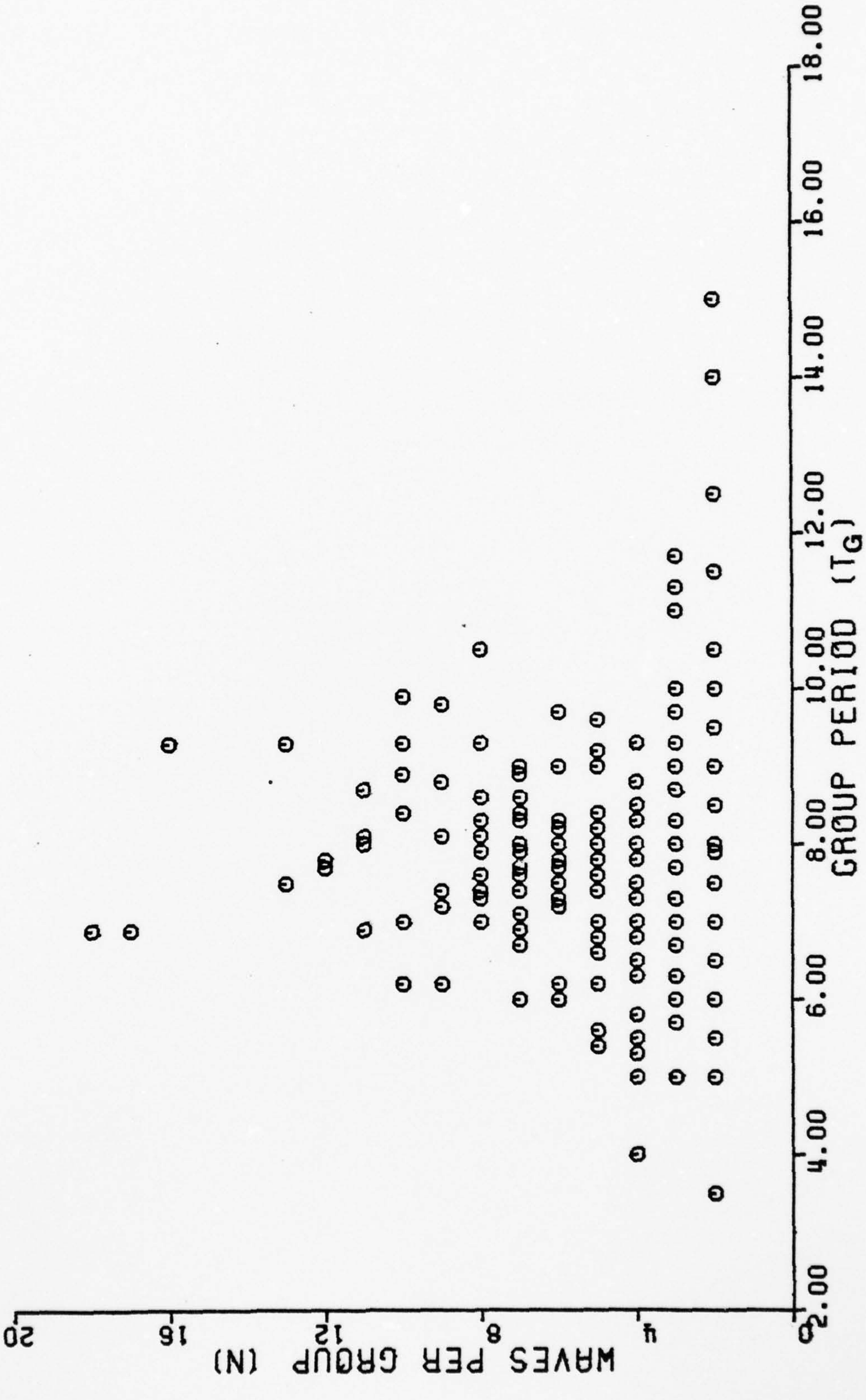

Figure 41. N vs T_G (6-10 sec band).

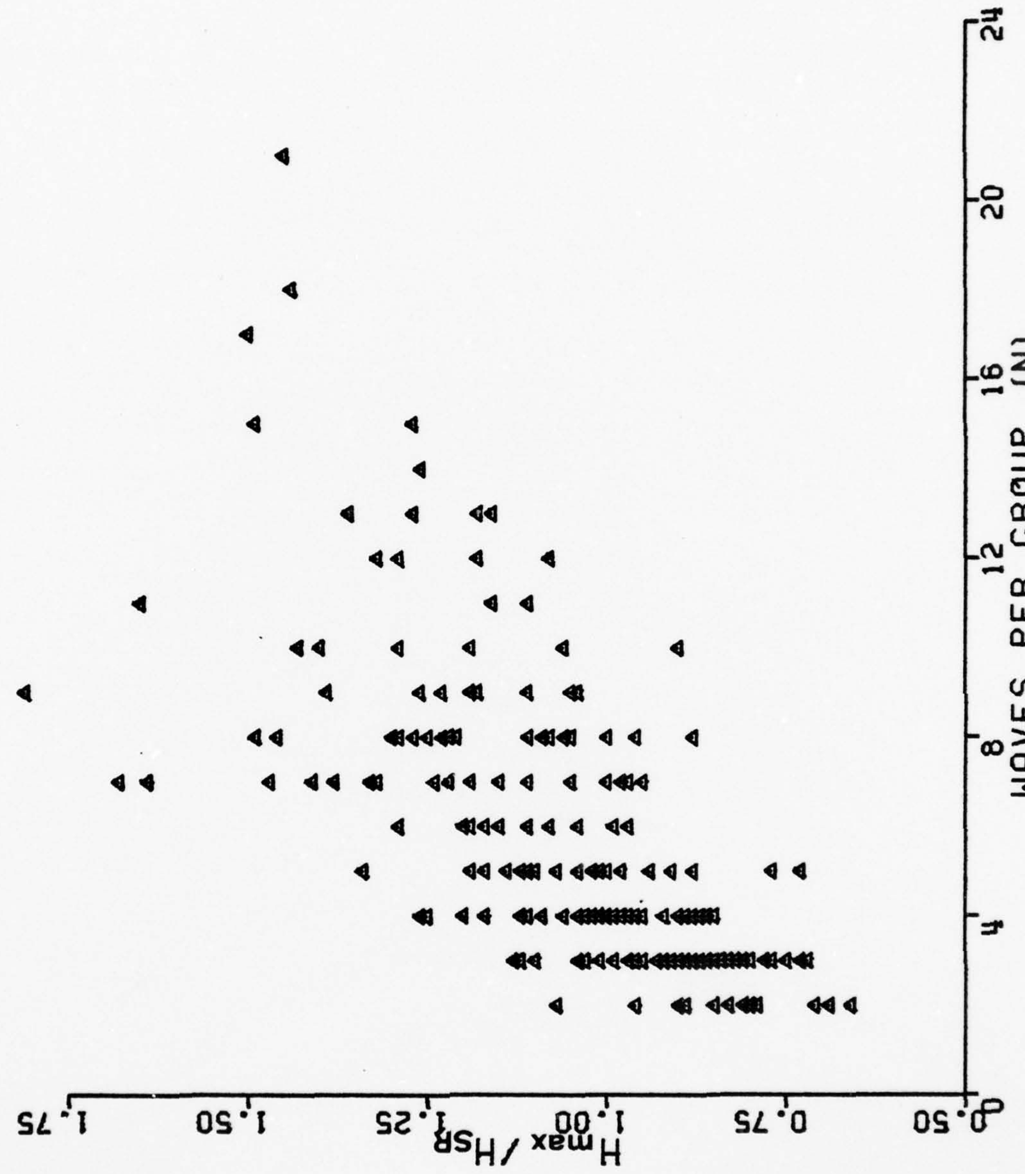

Figure 42. N vs H_{max}/H_{SR}.

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